A Resilience and Environmentally Sustainable Assessment Framework (RESAF) for Domestic Building Materials in Saudi Arabia

By

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Abstract

In Saudi Arabia, carbon footprint and energy use related to building materials, notably concrete in construction, have a significantly negative effect on the environment. Likewise, the impact of annual cooling and heating energy demands has an equally prominent role to play. These must all be assessed and benchmarked in order that reduction targets can be set. Saudi Arabia presents its own unique context and local conditions that create a challenge when utilising generic frameworks for assessing the environmental impact of domestic buildings. In meeting this aim, this PhD research presents a resilience and environmental sustainability assessment framework (RESAF) developed specifically for domestic buildings in Saudi Arabia.

The RESAF helps designers/builders to minimise the carbon footprints of building fabric and reduce the in-use energy demands of domestic buildings in Saudi Arabia. This study shows how this framework can be used to reduce the carbon impact of construction materials by approximately 23%, primarily by substituting a portion of cement for pulverised fly ash (PFA) or ground granulated blast furnace slag (GGBS). A reduction of 32% in the annual cooling and heating energy demand could also be achieved throughout a building's life simply by changing insulation type and thickness, and using triple-glazed windows. The importance of passing these alternative solutions through the resilience filter - to pressure test them in 3 archetypal futures (i.e. those related to Policy, Sustainability and Market Forces) - is highlighted, and helps ask questions about whether they are really fit-for-purpose whatever the future might hold. A user manual has been drawn for ease of RESAF utilisation, and a case study example is used to illustrate the framework and the potential carbon / energy savings that can be made through material choice(s) and long term use of the building. Application in a range of cities in Saudi Arabia has been considered in order to illustrate the influence of local context and conditions even with one country, particularly in terms of the cooling and heating energy performance. The RESAF was validated by consulting experts in Saudi Arabia via interviews and compared with past studies, all of which showed that it conformed to potential RESAF users' expectations.

Electronic copy of the Framework (RESAF)

The Microsoft Excel-based tool that accompanies the framework can be downloaded from the following links:

- Final version - password: 8090

https://drive.google.com/drive/folders/1z3jJOhpl-IJdPYcp5JPUnqZo5cw5eu9G

- Beta version - password: 8090

https://drive.google.com/drive/folders/1lgejo-q6kK7SpKgSC3k7-Deal0FR1_tP

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Abbreviations

A	Area
AC	Air Conditioning
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environment Assessment Method
CDD	Cooling degree-days
CIBSE	Chartered Institute of Building Services Engineers
CSFs	Critical Success Factors
D	Distance
d	Thickness
deQo	Database of embodied Quantity outputs
EC_{mat}	Embodied Carbon for material
EE_{mat}	Embodied Energy for material
EPDs	Environmental Product Declarations
GDP	Gross Domestic Product
GGBS	Ground Granulated Blast Furnace slag
HDD	Heating degree-days
HGV	Heavy Goods Vehicle
H_t	Total contribution to the heat gain or loss coefficient
ICE	Inventory of Carbon and Energy
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environment Design
MF	Market Forces
MQ	Construction Material Quantities
n	Rate of air changes per hour
NC	Necessary Conditions
P	Perimeter
PFA	Pulverized Fly Ash
PR	Policy Reform
PVC	Polyvinyl Chloride
Q_C	Annual cooling energy demands
Q_H	Annual heating energy demands
R_1	Thermal resistance for components of walls and roofs (materials layers)

RESAF	Resilience and Environmentally Sustainable Assessment Framework
R_{SE}	External surface resistance
R_{SI}	Internal surface resistance
SASO	The Saudi Standards, Metrology, and Quality Organization
SBC	Saudi Building Code
SEAM	The Saudi environmental assessment method
SGBF	The Saudi Green Building Forum
SGDs	Sustainable Development Goals
V	Volume
WTT	Well-to-Tank
yr	Year
λ	Thermal conductivity

1. Introduction

1.1. Background

Many authors have identified challenges or concerns with the current situation of Saudi Arabian domestic buildings with regard to their sustainability and resilience (Susilawati and Al Surf, 2011; Alrashed and Asif, 2014a; Aldossary et al., 2015a; Abd-ur-Rehman et al., 2018; Felimban et al., 2019). This may be because no home grown / developed building rating system previously existed which could take into account the country's unique combination (see page 6) (Attia, 2013; Shaawat and Jamil, 2014). That said, the National Committee for the Saudi Building Code (SBC) has been developing a green building code during the last few years, the official copy of which was released in April 2020 (SBC, 2020).

In Saudi Arabia, as with many other countries the construction sector negatively impacts the environment, using higher amounts of energy and material resources than any other sector (El Mallakh, 2015). At the same time this semi-arid region experiences some of the highest (extreme) temperatures (Al-Tamimi, 2017) around the world, reaching up to 50°C between June and July (Rahman et al., 2012). Therefore, it is not surprising that cooling systems currently account for around 66% of household electrical demands in the summer months (see Figure 1-1) (Krarti and Howarth, 2020). In 2018, energy demands from domestic buildings accounted for approximately 43% of the country's national electricity demand (see Figure 1-2) (General Authority for Statistics, 2018a). [Please refer to Chapter 2, Table 2-7 for national electricity demand by sector in Saudi Arabia between 2010–2018]. Given the significant amount of carbon that is related to its production this is an area where considerable improvement in terms of environmental impact could be made. However, significant body of knowledge has shown that the energy used from Domestic Buildings should not be viewed only from the point at which the building is occupied (Chastas et al., 2016; Motuzienė et al., 2016). In other words, the materials used within the building and the allied construction processes used to create them (i.e. embodied and embedded impacts) must also be given due consideration as they have a significant negative impact on the natural environment (Anand and Amor, 2017; Ramírez-Villegas et al., 2019).

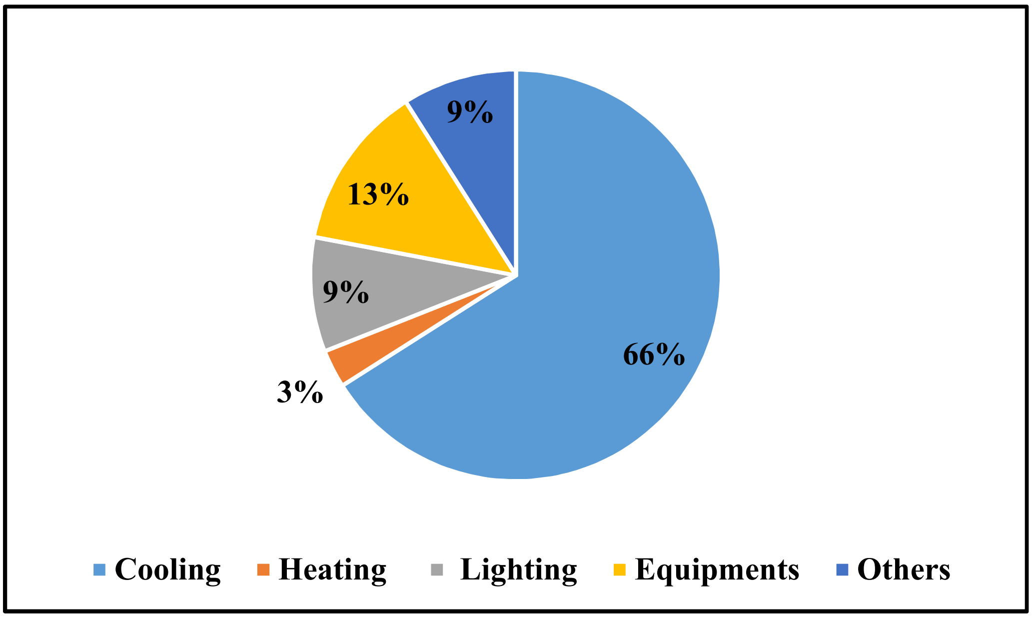


Figure 1-1 Electrical consumption in residential building by end-use in Saudi Arabia (Krarti and Howarth, 2020).

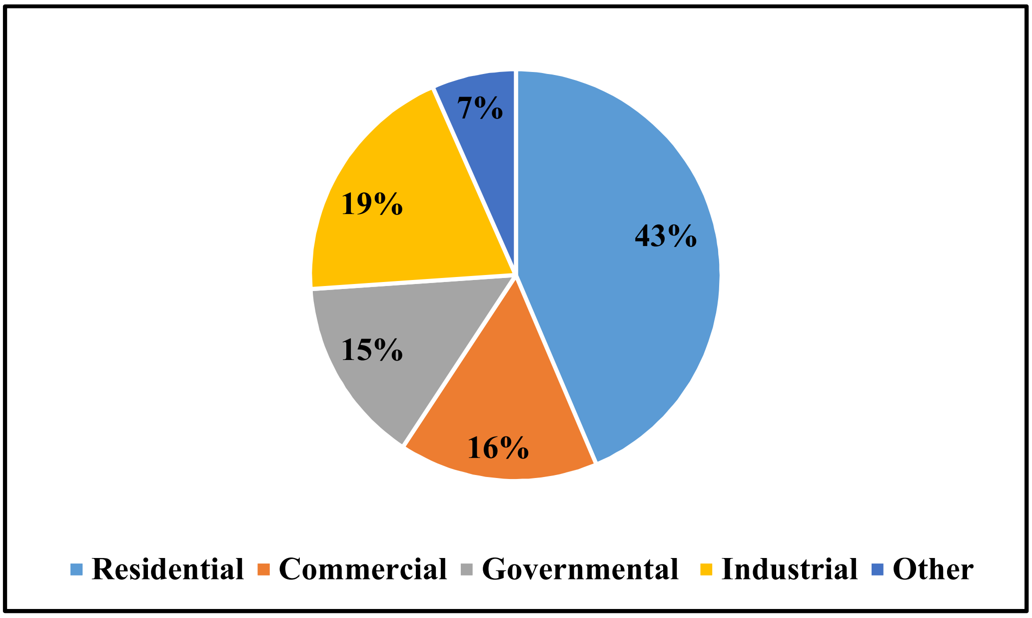


Figure 1-2 Percentages of national electricity demand per sector in Saudi Arabia (General Authority for Statistics, 2018a)

A large part of society's total carbon footprint is produced from the carbon emissions connected with the built environment (Fenner et al., 2018). Sustainable strategies for construction are attracting increased attention among scholars /practitioners and society as a whole due to their concerns over environmental damage and the world-wide depletion of resources (Govindan et al., 2016), not least oil. It has been argued that civil engineers have always engineered with society in mind and have thus always placed sustainability at the heart of their work (Rogers et al., 2012), therefore better consideration of the materials used therein should not be ignored.

For sustainable building practices to be implemented in Saudi Arabian construction, a balance must be struck between Environmental, Social and Economic performance (Akadiri et al., 2012). Notwithstanding when assessing the environmental sustainability of a building, it is widely considered that energy performance is the most important of these criteria (Berardi, 2012), not least with the advent of climate change, which strongly impacts the other two pillars. Therefore it is not surprising that this area receives the greatest attention.

At the same time the sustainable long-game in Saudi Arabia has to be considered – the impact on future generations to provide for themselves – and the longevity or resilience 'bounce-back-ability' to whatever the future might hold. Resilience in this context means that under changing circumstances, the function (in this case that of a domestic building) can still be delivered no matter what transpires (Lombardi et al., 2012). Future uncertainties are inevitable and an aspect which 'resilience proofing' as a concept should address (Sharifi, 2016). Certainties and uncertainties (perhaps better considered by asking a series of 'what if?' questions) include both expected and unexpected circumstances and outcomes, in other words both those which are natural or man-made (Rogers and Hunt, 2019).

In recent years, the number of natural disaster events in Saudi Arabia, such as dust storms and floods, have undoubtedly increased (Alshehri et al., 2015a). Viewing these concerns and challenges from two perspectives — sustainability and resilience — is extremely beneficial to future-proofing domestic building designs (Marjaba and Chidiac, 2016). However, for practitioners and scholars to successfully incorporate the concepts of sustainability and resilience together in a holistic way, requires new frameworks and tools to be developed and utilised within the built environment (Lizarralde et al., 2015). Reassuringly, many published studies have concluded that it is technically possible to incorporate resilience indicators and metrics with those for sustainability as the two work, for the most part, in parallel to each other (Roostaie et al., 2019).

In an ideal world, construction systems would incorporate robust resilience and sustainable standards underpinned with clear indicators and performance criteria (Burroughs, 2017) that work hand-in-hand. Not least because buildings are likely to encounter every changing circumstances as they emerge in the future. If they cannot adapt (by themselves or through minimal intervention) they will quickly reach their end-of life state and become obsolete (Markelj et al., 2014). In order to be resilient, individuals or entities must possess characteristics which enable them to maintain their identity when they are faced with stressful and unusual situations – ambitiously they may even emerge from such situations stronger than before (Böschen et al., 2019). Those working in construction design should, therefore, place a high priority on ensuring that new buildings are better able to cope with potential / stresses which future circumstances may impose on them. Moreover they need to be able to withstand the damage they may sustain from current and future climatic events (Champagne and Aktas, 2016). Added to this all new buildings, not least in Saudi Arabia, should also be constructed in line with local cultural and environmental conditions (Mortada, 2016).

The selection of construction materials is important as it contributes significantly to environmental sustainability (Al-Gahtani et al., 2016). The building industry has several unique features, such as extremely long design lifespans, the range of construction methods for aspects located both above and below ground (i.e. from foundations through to the super-structure) and a vast selection of construction materials to choose from (Rashid and Yusoff, 2015). Achieving a high positive impact with more sustainable construction is influenced greatly by the overall design and ultimately by decisions taken at the early stages of the overall decision-making process (Bakhoum and Brown, 2012). Research by Alaidroos and Krarti, (2015b) affirmed the need for promotion of energy saving for buildings by motivating and investing. These green shoots are beginning to emerge and there is recognition that changes are required in Saudi Arabia in the way domestic buildings are designed and constructed – starting with the materials they use. This current research project is a prime example. In a country such as Saudi Arabia, achieving a standard of zero-carbon homes as a concept would need to go beyond just the materials themselves and may ultimately become possible through the better utilisation of solar energy within the domestic sector (Abd-ur-Rehman et al., 2018).

Sustainability concerns related to material choices must be addressed in the early stages of building projects, when decisions are being made about building materials and techniques (Hasik et al., 2019). Additionally they need to follow the life cycle concept - thinking beyond the material that arrives at the construction site (Zhong and Wu, 2015). Huge demands for energy should be minimised as much as possible through material choices and better building design before applying other zero-energy home solutions (Alrashed et al., 2017). As a potential example of consideration given to construction materials, a former study achieved a 20% reduction in carbon by building using a design that re-used steel structure components (De Wolf et al., 2018).

In Saudi Arabia, efforts are being made to propose new regulations and government policies, to help drive changes in building design and overall efficiency. When combined with adoption of energy-efficient technologies within the home, which are readily available, the net energy demand can be reduced. However further reductions can be achieved if energy consumption habits of Saudi citizens are considered. This behavioural aspect, whilst not a focus of this study must be improved, driving down what is a high demand – outside of the building fabric and the technologies adopted within the building itself. This is important in combination to material choices if a net overall positive impact is to be achieved (Asif, 2016) in both the short and long-term.

Whilst there are many tools available for measuring sustainability and resilience (Shaawat and Jamil, 2014; Al Surf, 2017), questions exist about whether these tools meet the local conditions and context for Saudi Arabia. One of the difficulties is that there are reported contradictions between energy performance figures once the building is occupied (operation stage) as compared to the simulated long-term performance suggested in the design stage (Alyami et al., 2013). Furthermore, a study by Alshuwaikhat and Mohammed (2017) asserted that a methodology which is suitable for one country cannot necessarily be transferred successfully to another, because of the different contexts existing in each respective country – for example a semi-arid region like Saudi Arabia compared to somewhere like the United Kingdom. This may go some way towards explaining why such discrepancies exist. A number of influential factors (unique combination) in Saudi Arabia, not necessarily an exhaustive list, are listed below and need to be taken into account (Attia, 2013):

- Policies and regulations,
- Culture and traditions,
- Public opinion / behaviour,
- Environmental factors,
- Climate,
- Geographical characteristics,
- Systems and materials used in construction,
- How resources are consumed, and
- The prospect for integration of renewable energy.

Saudi government organisations have also been paying greater attention to sustainability in recent years (Alrashed and Asif, 2014a; Alyami et al., 2015). A tangible example of this is the *Saudi Vision 2030*, which takes a huge positive step towards implementing sustainability over a fourteen year period (Government of Saudi Arabia, 2016).

In addition to all of these previous requirements, it is recommended that tools tailored for the sustainable assessment of Saudi Arabian homes be developed from within (Taleb and Sharples, 2011; Aldossary et al., 2015b). Additionally, it is recommended that such innovative tools be employed by building owners so that they can manage construction decisions (including renovation projects) sustainably, especially when they own a large portfolio of buildings (Nielsen et al., 2016).

In meeting this need the current research presents a Resilience and Environmental Sustainability Assessment Framework (RESAF) for Domestic buildings. RESAF is designed to target building practitioners (e.g., architects, designers, builders, engineers, contractors) or those interested in the building field (perhaps research bodies, for example). Ultimately it is hoped that RESAF will help building practitioners minimise the carbon footprint of the building fabric and thereby reduce in-use energy demand of domestic buildings in Saudi Arabia.

1.2. Aim and objectives

This research aim is

'To develop a framework for assessing both the resilience and sustainability of construction materials used in domestic buildings in Saudi Arabia'.

In order to achieve this aim, this study will pursue the following five objectives in Table 1-1.

Table 1-1 Objectives and output of the research

No	Objectives	Methodology (M) stages	Research outputs	Chapters number
1	To critically review the current state of the sustainability and resilience in Saudi Arabian domestic buildings and existing assessment methods.	Review the existing literature on related topics.	A gap of knowledge in the existing literature.	2
2	To develop a Resilience and Environmentally Sustainable Assessment Framework (RESAF) for Domestic Building Materials in Saudi Arabia.	Designing the RESAF through selecting the (main factors and basic data).	A beta version of RESAF and its user manual (an explanation of the functioning of the framework)	4
3	To Apply RESAF to an actual residential building in Saudi Arabia	Applying a domestic building in the design stage, using a real case study.	Results of the case study application.	5
4	To validate the RESAF and its outcomes through consulting construction and building professionals in Saudi Arabia.	- Conducting interviews with experts in the construction and building field. - Comparing the RESAF outcomes (results) with other available assessments, and Saudi Arabian results from the literature.	- Feedback about the RESAF design and application. - Notes about the RESAF design and application.	5
5	To refine the RESAF and its application based on the feedback from the consultation.	Revising the RESAF beta version based on feedback and notes obtained during the validation step.	A final version of RESAF and its user manual.	5

1.3. Contributions of this study

The merits of this research, and its contributions to the existing literature, can be summarized as follows:

1. It proposes a framework, RESAF, that can be used in the early design stage of domestic buildings to assess both the environmental sustainability of the construction materials and the future resilience of the materials. It should be noted that this kind of framework is not currently available in Saudi Arabia;
2. It describes the first framework in the country that applies resilience assessment to buildings, particularly domestic buildings; and
3. It reports the first framework in the country that considers both sides of the environmental effects related to construction materials – in other words, how to select construction materials in order to reduce carbon emissions and energy usage for 1) the materials' embodied impacts and 2) the long-term cooling and heating energy demands of domestic buildings.

1.4. Organization of the thesis

This thesis is divided into six chapters. The following is a brief description of the content of each chapter. Table 1-1, shown previously outlines the relationship between the study's objectives, research questions, the methods selected, and the related chapters.

Chapter 1. Introduction. This chapter describes the background of the study, presenting an overview of sustainability and resilience in domestic buildings, challenges and concerns, the current situation of in-use energy demands, the importance of selecting construction materials, issues with available assessments and influential factors in Saudi Arabia (i.e. context and conditions). It then outlines the study aim and objectives and briefly mentions the methodology steps and outcomes.

Chapter 2. Literature Review. This chapter provides a general overview about sustainability and resilience in isolation and combination. It then outlines the Saudi Arabian background and reviews sustainability and resilience in the context of domestic buildings in the country. Finally, it examines international and local tools and guidelines for sustainability and resilience. All of this was done in order to determine the knowledge gap about domestic buildings in the literature.

Chapter 3. Methodology. This chapter begins with an overview of the five methodological steps used to complete this research (see Figure 3-1); it also presents the general requirements that were considered when developing the RESAF (see Table 3-1). This is followed by an explanation of the research methods of each step in general terms (specifics are detailed in Chapter 4).

Chapter 4. Development of the framework (RESAF). This chapter contains an in-depth explanation of RESAF, outlining how the two filters were designed regarding the data used and calculations made. The first filter comprises sustainability (noting that environmental sustainability is the focus) with three stages: proposed construction material selection for a domestic building (cradle-to-gate), transport selection from gate-to-grave and U-value calculations for domestic buildings. The second filter comprises an urban future assessment to determine the future performance of the selected materials. It also outlines the user manual and the information required to use the framework (including a detailed domestic building case study as an illustrative example). Finally, it explains how the final version of the RESAF was achieved by illuminating the validation process: conducting interviews (i.e. interview outlines and questions) and comparing its results with past studies.

Chapter 5. Results and discussion. This chapter presents and discusses the study findings after applying a domestic building case study to RESAF; it also proposes alternative solutions (materials choices) within the case study. It discusses the outcomes of the validation process: the interviewers' response and positioning the framework within past studies. Finally, it presents the influence of validating the RESAF and outlines RESAF's potential for helping stakeholders to select appropriate materials for environmental sustainability and resilience.

Chapter 6. Conclusions. The last chapter summarises the PhD study, reflecting upon the objectives and methodological steps laid out in Chapters 1 and 3 that were used to create the RESAF. It also reports the value this research adds to the gap in the literature presented in Chapter 2. In addition, it outlines the study limitations, particularly in terms of the RESAF's scope. Finally, it puts forth recommendations for future work.

2. Literature Review

This chapter critically reviews the following concepts from the literature:

2.1. Sustainability and resilience as concepts in isolation and combination;

2.2. Saudi Arabian background;

2.3. Sustainability in the Saudi Arabian context;

2.4. Resilience in the Saudi Arabian context;

2.5. The concept of integrated sustainability and resilience in Saudi Arabia;

2.6. Literature review of the methodological process; and

2.7. Summary.

The review looks at sustainability and resilience as concepts as well as their application through tools and guides, with a specific review of their use in Saudi Arabia. This review was conducted to identify gaps in the current literature concerning sustainability, resilience, and domestic building materials in this country. Studies that consider sustainability and resilience in the context of Saudi Arabian domestic buildings were identified through a systematic review, see Section 2.6. These studies have been referred to and integrated within the content found in Sections 2.3 to 2.5.

2.1. Sustainability and resilience as concepts in isolation and combination

2.1.1. Sustainability

Brundtland (1987), when addressing the United Nations, defined sustainability as:

'The ability of the present generation to meet their needs without endangering or compromising the ability of future generations to meet their own needs'.

Whilst there are many definitions within the related literature (see Walton, 2005), this is the one that occurs most frequently (Mensah and Casadevall, 2019). As defined by Kibert (2005) and Al-Yami and Price (2006), sustainability involves *'intergenerational justice'*, as it respects the future generations by maintaining the planet, in other words, the environmental function, such as the availability of resources and quality of life. Longevity can be linked to sustainability. Roostaie et al. (2019) maintains that the greater the length of time for which a structure or product can be preserved, the greater its sustainability will be. Most researchers argue that environmental, social, and economic factors are inherent components for improving sustainability (Milne and Gray, 2013; Thomas, 2015). The following Venn diagram represents the three factors centring on sustainability, which is universally accepted as a sustainability illustration (Purvis et al., 2019), see Figure 2-1. Mensah and Casadevall (2019) adopted a generalisation of these three aspects based on Porter and Van Der Linde (1995) and Olawumi and Chan (2018); the explanations are as follows:

- **Environmental sustainability** is determined by factors relative to planning and land use combined with ecological and biodiversity conservation. It takes into consideration the ability of the ecosystem to support human wellbeing, especially with regard to materials, land, water, and air quality.
- **Economic sustainability** is determined by suitable production, distribution, and consumption. It is determined, for example, by the effective use of resources to maximise the profitability and market value, the development of materials and local products, and the encouragement of recycling and reuse of materials.
- **Sustainability of society** relates to the social wellbeing of individuals. These include public awareness, maintenance of human rights, efficient educational systems, upholding the law, efficient healthcare systems, and a good working environment.

Figure 2-1 Three aspects of sustainability (Environmental Protection Agency, 2016b)

The sustainability principles were established in the construction industry by Kibert (1994) to save limited resources and establish a healthy environment (Hill and Bowen, 1997). Sustainable construction can be defined as creating structures that have adhered to environmental guidelines and have used resources effectively to ensure the preservation of those qualities from the design concept through usage to eventual deconstruction (Environmental Protection Agency, 2016a); see Figure 2-13, Section 2.5.1.1 for the building and construction life cycle. Around one-third of the global population's consumption of materials and energy is because of the construction industry (Olawumi et al., 2020). This industry also generates 30% to 40% of the total global solid waste in terms of weight (Jin et al., 2017; Islam et al., 2019). This huge consumption applies to the construction of domestic buildings (Alrashed et al., 2017); see Section 2.2 for specific data regarding Saudi Arabia. Adabre et al. (2020) cited the devastating effects of uncontrolled waste and the use of inappropriate materials with the resultant retrogression of global warming by the increased concentration of greenhouse gases, urban heat islands, floods, and the harmful effect on air quality that can lead to increases in asthma and cardiovascular diseases. This indicates an urgent need in recent years to establish sustainable construction practices. Therefore, it is commonly reported that the construction industry must give priority to lowering emissions and avoiding environmental damage as key driving forces for sustainable construction (Kaziolas et al., 2017; Udomsap and Hallinger, 2020), especially from an environmental perspective (Park et al., 2017). This affects all countries, especially those that are developed (Araújo et al., 2020), and this includes Saudi Arabia, which is the subject of this study (RESAF).

Somogyi (2016) identified an early use of sustainability resulting from a timber shortage in medieval Europe in the eighteenth century. Accordingly, to preserve scarce resources, *'the careful management of sustainable forestry resources'* was undertaken to determine the best usage of available timber (Somogyi, 2016) Within the literature, raw materials are considered fundamental components of buildings as well as the starting point for addressing environmental concerns within the construction industry (Bakhoum and Brown, 2012; 2013; 2015). Thus, as observed by Akadiri et al. (2012), Akadiri (2015), and Pongiglione and Calderini (2016), the characteristics of the available construction materials play a critical role in enhancing material sustainability. Hunt et al. (2012) listed the need to maintain the natural environment, which is the greatest economy in resource consumption, and to improve social utility as factors that relate to the union of sustainable buildings with the natural environment, thus lessening degradation of the environment. Švajlenka and Kozlovská (2018) and Goh et al. (2020) stated that selecting sustainable construction materials is possible by applying environmental, economic, and social criteria, as has been discussed in general terms earlier in this section:

- Sjöström and Bakens (1999) identified the first criterion as environmental sustainability, whereby the building, throughout its entire lifecycle, remains in harmony with its natural surroundings. For example, a design strategy incorporates the use of sustainable materials in conjunction with a structural design that selects materials with less environmental impacts (Pongiglione and Calderini, 2016; Kupwade-Patil et al., 2018);
- Abidin (2010) and Landolfo et al. (2011) identified the second criterion as economical sustainability, whereby both the construction costs and the maintenance of a building are considerably reduced during its lifecycle, thereby allowing financial gain for the project stakeholders; and
- Social sustainability, an equally important criterion, allows for the general comfort and security of residents and users. It may be affected by the quality of the construction with regard to fireproofing, sound insulation, and the aesthetic values of the structure (Landolfo et al., 2011; Goh, 2017).

The research framework (RESAF) focuses on the first criterion of environmentally sustainable materials, specifically, on carbon and energy measures. Other details about sustainable construction materials in Saudi Arabia can be found in Section 2.3.1, and for information about Life Cycle Assessment (LCA), see Section 2.5.1.1.

2.1.2. Resilience

The term 'resilience' has been implemented and developed by many disciplines in the past, including the ecological, engineering, and organisational sectors; therefore, there is no simple or unifying definition of this term (Madni and Jackson, 2009; Hassler and Kohler, 2014; Hollnagel, 2014). Historically, the term has been established in the English language since the seventeenth century and has been used at later dates by scholars (McAslan, 2010). According to McAslan (2010) and Hollnagel (2014), the term 'resilience' was first used by the scholar Tredgold (1818) to justify the ability of some types of wood to withstand unexpected loads without breaking. Mallet (1856) then used the term '*modulus of resilience*', which assessed the material in the context of withstanding strong conditions.

During the last 50 years (Table 2-1), there have been different definitions proposed by McAslan (2010) and Bhamra et al. (2011), which are based on varying disciplines and timeframes. Regarding these definitions, Bhamra et al. (2011) raised several questions about resilience as *'a measure, a feature, a philosophy or a capability?'* However, McAslan (2010) stated that although there are many definitions, they share some characteristics, such as recovery from abnormal events and preparation or adaption to face changes. According to Hassler and Kohler (2014), this can be summarised as a core element of resilience in responding, adapting, and evolving.

Table 2-1. Development of resilience definitions extracted from McAslan (2010) and Bhamra et al. (2011)

Context	Definition	Author and year
Ecological systems	*'The measure of the persistence of systems and of the ability to absorb change and disturbance and still maintain the same relationships between state variables'*	Holling (1973)
Ecological systems	*'The speed at which a system returns to a single equilibrium point following a disruption'*	Tilman and Downing (1994)
Organisational	*'The fundamental quality to respond productively to significant change that disrupts the expected pattern of event without introducing an extended period of regressive behaviour'*	Horne and Orr (1998)
Disaster management	*'Resilience describes an active process of self-righting, learned resourcefulness and growth'*	Paton et al. (2000)
Individual	*'Resilient individuals' possess three common characteristics. These include an acceptance of reality, a strong belief that life is meaningful and the ability to improvise'*	Coutu (2002)
Ecological systems	*'The capacity of a system to absorb a disturbance and reorganise while undergoing change while retaining the same function, structure, identity and feedback'*	Walker et al. (2004)
Engineering	*'The ability to sense, recognise, adapt and absorb variations, changes, disturbances, disruptions and surprises'*	Hollnagel et al. (2006)
Physical systems (materials)	*'Ability of a material to absorb and release energy, within the elastic range'*	Gere and Goodno (2009)

From the range of the definitions of resilience in Table 2-1, it is understandable that the meaning of the term 'resilience' has transformed over time (Hassler and Kohler, 2014). Martin-Breen and Anderies (2011) stated that the reason for this involved the *'scale and level of precision'* as, sometimes, resilience is considered in specific scales like engineering or as individual or organisational traits. Moreover, looking at resilience in the past, for example, researchers have explained it as the need for the completed structure to endure extrinsic disturbances and be able to regain its previous state after any such disturbance, as in the definitions by Holling (1973) and Tilman and Downing (1994) (see Table 2-1). However, with respect to this definition, resilience now relates to more than the system merely reverting to its previous state (Bosher, 2007). According to Redman (2014), change happens, and it is necessary to fortify the system against any subsequent disturbances to minimise damage, as defined by Walker et al. (2004) and Hollnagel et al. (2006) (see Table 2-1) and Lombardi et al. (2012) (see Table 2-3). For clarification, in terms of the variety of definitions, based on Hollnagel (2014), for the practical use of resilience, see the following four descriptions:

1. Resilience was used in 1818 with regard to the substance of materials used. It was intended to describe the intrinsic qualities of the constituents and was consequently referring to a static system;
2. Resilience as a feature of ecological systems involves a system that is dynamic in that it can react to a certain situation even reconstructing its mode of operation; however, this is not in an anticipatory manner or with set intentions but only as a concept of a living or dynamic system;
3. As a psychological system, it is able to relate to earlier experience and consequently respond to and, to an extent, anticipate further activities; and
4. As a result of dynamic and intentional systems, resilience can operate in a business function and especially in engineering resilience. Anticipation is a key factor in both instances, and it has an important function, especially in situations where resilience is required. Such instances often occur quickly and can require almost instantaneous reactions.

In the context of a resilient building, the structure must be able to carry on into the future and be able to withstand various certainties and uncertainties (Lombardi et al., 2012). These circumstances need to be incorporated into the concept of resilience

(Sharifi, 2016), with Rogers and Hunt (2019) citing some of these as being expected and unexpected acts of nature or those that are manufactured (man-made). To withstand these future disturbances, a resilient building must have the capacity to remain fully functional while adapting to any occurrences (Martin-Breen and Anderies, 2011). However, Bocchini et al. (2013) stated that this requirement does not refer just to structural resilience. The recovery of a building following a major natural disaster has a marked influence concerning the socioeconomic and political conditions within the community in which it is found (Rogers et al., 2012). In a related example, human beings need to be resilient to maintain their identities when subjected to demanding and abnormal situations—the coronavirus disease (COVID-19) in 2020 is the most recent example of this (human identity includes an acceptance of reality, a strong belief that life is meaningful and that humans have the ability to improvise (Coutu, 2002)]. Böschen et al. (2019) maintained that it may even strengthen their resolve following the experience, whereas Bunz et al. (2006) stressed the need for there to be interdependency between the community and the building to provide adequate resilience.

Theoretically, according to Burroughs (2017), resilience standards and performance criteria should be incorporated into construction systems. An example offered by Middleton (2018) is when Polyvinyl Chloride (PVC) is used in water pipes, which can last for 100 years, as the material is resistant to weather distributives. The product can also be used as cable insulation for internet wires. In these cases, there are social benefits, as all the facilities are returned positively to the community. Likewise, Berardi (2012) argued that the success or failure of how materials are used depends on several factors, which include the level of technology being used, social and economic conditions, and the relationship between local communities and political leaders. Therein the evidence of key drivers of change (e.g., PESTER – political, environmental, social, technological, economic, and regulatory) is highly apparent. However, as with any assessment framework (such as with sustainability), it is necessary to appreciate the need for reliable holistic and meaningful benchmarks, indicators, and measures (Hunt et al., 2007).

2.1.3. *Combining sustainability and resilience*

Sustainability and resilience are both theoretical concepts and are diverse in their definitions and meanings (Derissen et al., 2011). Table 2-2 illustrates the different and sometimes contrasting elements of sustainability and resilience, which have been extracted from Redman (2014). Prior to this, Hill and Bowen (1997) had observed that these concepts had attained growing importance in their application to the building industry, from the planning stage to construction, occupation, and eventual demolition.

Table 2-2. Comparing sustainability and resilience elements (Redman, 2014)

Resilience	Sustainability
Change is viewed as normal, and there is more than one stable state.	Sustainability sets a vision for the future and works to turn it into a reality.
Experience is adaptive and passes through cycles.	Sustainability utilises a transition management approach.
The origin of resilience is in ecology, as it aims to sustain ecosystems.	The origin of sustainability is in the social sciences, which view society as concerning.
Its main concern is maintaining system dynamics.	Its main concern is interventions that result in sustainability.
The outcomes of change are emergent and open-ended.	The outcomes of change are pre-determined.
Stakeholders focus their input on desirable dynamics.	Stakeholders focus their input on desirable outcomes.

This continuing development was confirmed by Fisher et al. (2012), who observed that there have been extensive studies to determine the relationship between compatibility and discord in relation to sustainability and resilience, especially in regard to design, construction, and building functionality (see, for example, Lizarralde et al. (2015), Phillips et al. (2017), Hasik et al. (2019) and Roostaie et al. (2019)). Tables 2-3 and 2-4 indicate the impact and origins of the resilience and sustainability paradigms that are currently used within the construction industry.

Effective resilience is a combination of structural strength to sustain a building against the natural elements and the ability of residents to adopt timely and appropriate recovery action for their building (Burroughs, 2017). Therefore, it is of interest to understand whether it is technically feasible to have a fully integrated framework with benchmarks, indicators, and metrics that could be adopted within the building 'materials' sector. As Wholey (2015) maintained, it is crucial that any such assessment framework be applied before any construction project commences; this view is also upheld by Hunt et al. (2008). Roostaie et al. (2019) found that the majority of studies believe such an assessment to be possible and recommend that the sustainability metrics include the majority (if not all) of the resilience indicators. Bocchini et al. (2013) stated that within both fields, there is an overall requirement to make the most effective use of materials, structural design, and management plans; additionally, there is a need to incorporate both maintenance and operations while considering their effects on society. Matthews et al. (2014) recommended that sustainability as well as resilience be integrated into the assessment and design of buildings. In their view, this would involve the following actions:

(1) Conserve future resources;

(2) Protect investment in sustainable structures and infrastructure;

(3) Ensure that sustainable developments continue to function for their design life and continue to reap the benefits of sustainable design; and

(4) Preserve the stability of social and economic networks within communities.

The evaluation and development of new sustainable materials to better support resilience is an ongoing necessity (McManus et al., 2010) in order to design new products and systems that are suited to meet users' requirements. However, the area of developing sustainable products still has unresolved questions that require further research, for instance, as a generic example, how to establish a balance between environmental impacts and gross domestic product (GDP) in the future (Chang et al., 2014); see Figure 2-6 in Section 2.2 for Saudi Arabian GDP in the construction sector. A specific example of this study is ensuring the long-term solution (Xu et al., 2015), in other words, the future ability of the proposed sustainable solutions for construction materials. Likewise, as suggested by Marjaba and Chidiac (2016), there will always be a need to improve and revise processes and products to strengthen framework resilience. Therefore, further research is needed to advance future adaptive resilient and sustainable strategies within a framework, for example, the framework, RESAF, in this research study.

Table 2-3 Impact and origins of the resilience and sustainability paradigms used in the construction industry (modified and extended by the researcher from Lizarralde et al. (2015)) – part 1

Aspects	Sustainability	Resilience
Advocated definition by the researcher	According to Brundtland (1987), sustainability is defined as *'the ability of the present generation to meet their needs without endangering or compromising the ability of future generations to meet their own needs.'*	Lombardi et al. (2012) considered that '*When a structure can still function under changing circumstances, it can be considered resilient.'*
Components	Marchese et al. (2018) proposed that the considerations which form the so-called 'bottom line' comprise sustainability. These are environmental, economic, and social concerns.	Marchese et al. (2018) viewed resilience as a system that can withstand potential threats while concurrently adjusting to the effects of persistent stress or disruption.
Theory origins	The idea of sustainable development originated in a report put forth by Brundtland in 1987.	Holling et al. (1973) defined the concept of adaption in ecosystems.
The field the idea originally emerged in	Sustainability emerged from the discipline of economics	Resilience emerged from: (1) Disaster risk reduction in the 2000s; (2) Ecology in the 1950s; (3) Manufacturing in the early 20th century; and (4) Psychology in the 19th century.
Key concepts that have been incorporated into built environment policy	Key concepts include green, sustainable cities and neighbourhoods; the use of products that are environmentally friendly; and designing with eco principles and environmental impacts in mind.	Key concepts include resilient cities as well as risk reduction, climate change adaption, and ecosystem balance.
Tools to operationalise the paradigm in the built environment	These tools include certification for green buildings as well as environmental and sustainable development.	These tools include programmes for the reduction of risk, plans for contingencies, mitigation, buffer zones, and reconstruction.

Table 2-4 Impact and origins of the resilience and sustainability paradigms used in the construction industry (modified and extended by the researcher from Lizarralde et al. (2015)) – part 2

Aspects	Sustainability	Resilience
Targets in the built environment	These targets include minimising the use of fossil fuels, non-renewable resources, and energy consumption in general as well as reducing greenhouse and carbon emissions, pollution, and waste control.	These targets include the construction of disaster-resistant buildings, enhanced capacity for adaptivity, the provision of redundant system components, and efficient reconstruction.
Joint considerations	Lew et al. (2016) stated that there is need for a balance between humans and nature while emphasising fighting climate change as part of the parallel aims of the two concepts. In today's construction industry, there are great opportunities to develop practices for sustainability that are more finely aligned with methods that promote resilience. For example, sustainability can be framed as a crucial function of a system, policy, or project, and one that must be maintained during and after a disturbance (Marchese et al., 2018). There is little consideration for long-term solutions in resilience thinking in order to ensure that today's resources are available in equal or greater magnitude in the future (Xu et al., 2015). Greater resilience ensures greater durability (Wu and Low, 2010), and a more resilient building with an extended lifecycle that defers the detrimental effect of demolition is a more environmentally friendly solution. Resilience, where the crucial stage has not been reached, allows buildings, even those that have been subjected to disturbance, to be able to function even though their resources will be depleted and no longer accessible to the same degree as previously (Xu et al., 2015). Today, the academic world is seeking to educate and encourage the construction industry about adopting strategies that apply economic and social measures and techniques that combine lifecycle analysis and decision-making (Bocchini et al., 2013).	

2.2. Saudi Arabian background

Before assessing Saudi Arabia’s approach to sustainability and resilience, it is useful to outline some general features of the country. It borders with Kuwait in the northeast; Yemen in the south; Jordan and Iraq in the north; Bahrain, Qatar, and the United Arab Emirates in the east; and Oman in the southeast. It also borders the Arabian Gulf from the east side and the Red Sea from the west side (General Authority for Statistics, 2018b). See Figure 2-2 for a map of Saudi Arabia.

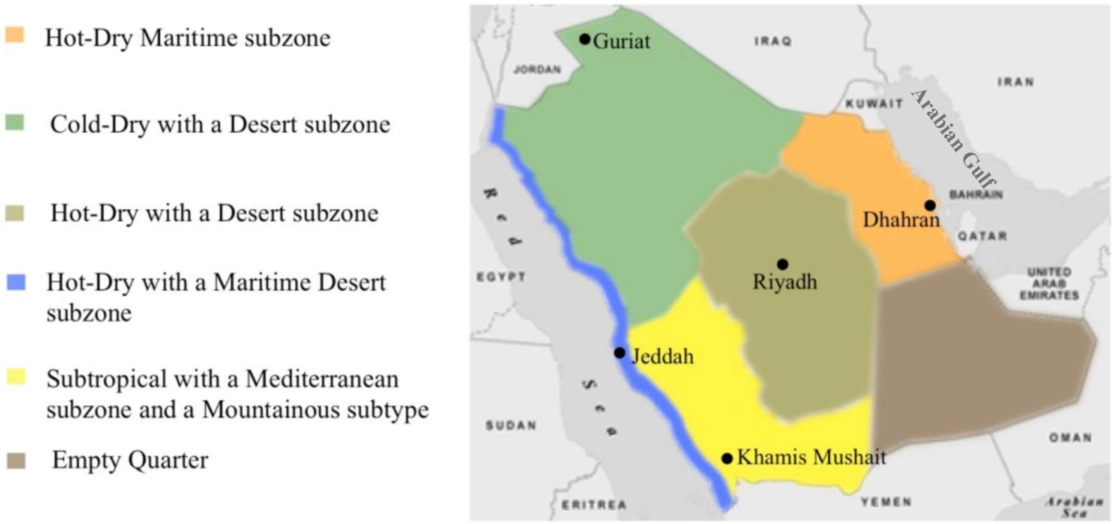


Figure 2-2 Map Saudi Arabian climate zones based on Said et al. (2003) and Alrashed and Asif (2015a)

Saudi Arabia accounts for approximately 80% of the total land area of the Arabian Peninsula, covering 2,000,000 m^2. It possesses a range of topographical features from arid desert to mountains, and therefore encompasses a range of climates (General Authority for Statistics, 2018b). In Figure 2-2, Alrashed and Asif (2015a) presented a map showing that Saudi Arabia can be divided into six zones (climate information was taken from Said et al. [2003]). There are two notable points in this zone classification. First, there is a zone called cold-dry with a desert subzone, which is considered cooler than the other zones in Saudi Arabia. Second, there is a zone called empty quarter, which is an uninhabited zone.

However, in general, summers are hot, and winters are cold (General Authority for Statistics, 2018b). See Table 6 in Appendix E for the monthly maximum and minimum temperatures for selected Saudi Arabian cities in 2019. The Saudi Energy Conservation

Code for Low-Rise (Residential) Buildings (SBC 602) divided the country into three thermal climatic zones: extremely hot, very hot and hot; see Figure 2-3 (SBC, 2018a). These zones were divided based on the cooling degree days (CDD): zone 1 (white) is extremely hot with CDD 10°C greater than 5,000; zone 2 (orange) is very hot with CDD 10°C greater than 3,500; and zone 3 (red) is hot with CDD 10°C less than 3,500 (see Section 4.2.3.4 for more information about the meaning of degree days and how they are used to calculate the annual energy demand; see also Table 7 in Appendix E for data about cooling and heating degree days for selected Saudi Arabian cities.

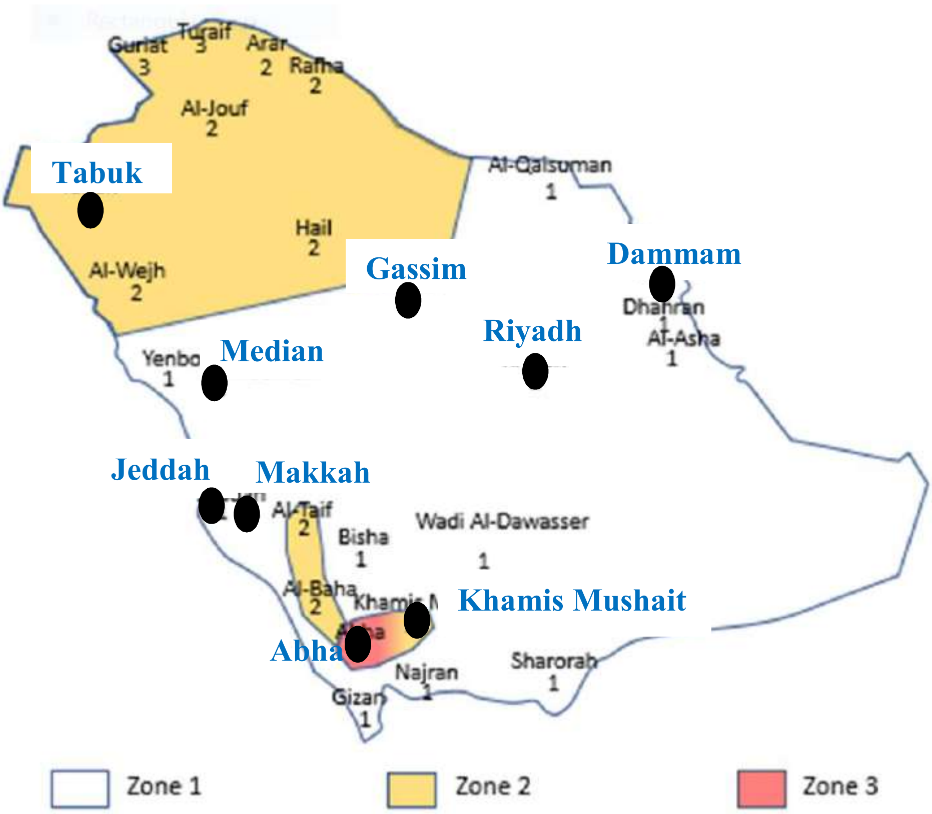


Figure 2-3 Map of Saudi Arabian thermal climate zones (SBC, 2018a)

This is a clear indication that a hot weather mainly influences the country's climate. The case study in this research focuses on a domestic building located in the city of Dammam; however, other cities (Gassim, Jeddah, Khamis Mushait, Makkah, Median, Riyadh, Tabuk and Abha) representing the three zones are also selected to explore other cities' influence using RESAF (see Figure 2-3).

Saudi Arabia relies mostly on oil and natural gas as its energy (electricity) source. Alshibani and Alshamrani (2017) and Felimban et al. (2019) suggested that because of the country's annual growth of electricity usage, which is between 5% and 8%, the future of oil and gas production and the domestic consumption of oil and gas in Saudi Arabia will reach parity in 2035. In 2018, it was reported by the Electricity & Cogeneration Regulatory Authority (ECRA) that the country consumes 2,246 million British thermal units (MMBTU) of fuel to generate electricity; the source of this fuel is 55% oil and 45% natural gas. See Figure 2-4 (ECRA, 2018).

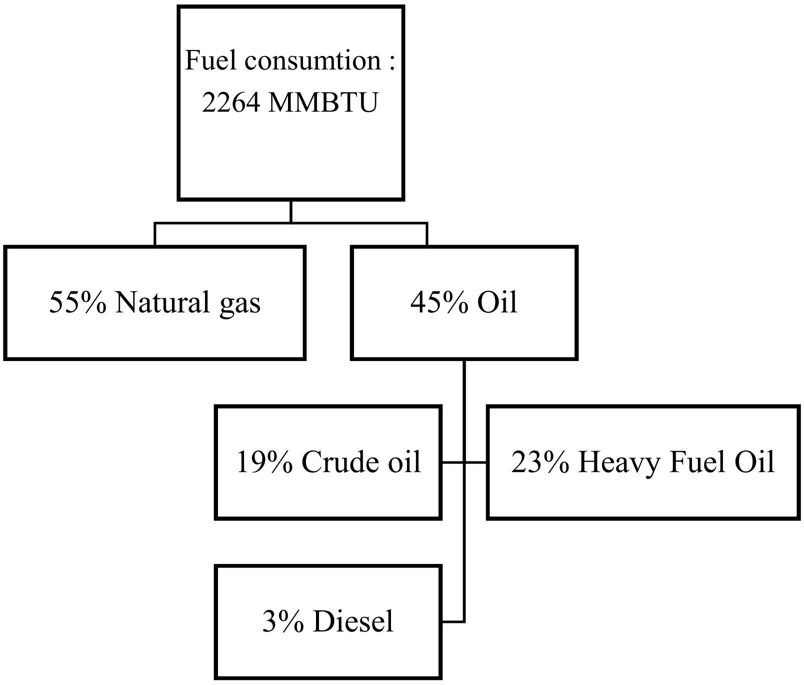


Figure 2-4 Saudi Arabian sources for electricity generation

Alrashed and Asif (2015b), Alshehry and Belloumi (2015), Al-Douri et al. (2019), and Amran et al. (2020) noted that this situation will only exacerbate the country's major problems with the negative environmental impacts because those fuels are the primary source of Saudi Arabia's large carbon footprint. Table 2-5 shows the total and per capita national electricity consumption between 2010 and 2018 in the country (General Authority for Statistics, 2018c) and the associated total and per capita carbon footprint from electricity consumption.

Table 2-5 Saudi Arabian electricity consumption and carbon footprint between 2010 and 2018

Years	Electricity consumption		Carbon footprint	
	Total (GWh)[1]	Per capita (kWh)[2]	Total ($MtCO_2e$)[3]	Per capita ($KgCO_2e$)
2010	218,254	7,962	158	5,780
2011	225,509	8,004	164	5,811
2012	246,610	8,534	179	6,196
2013	262,685	8,871	191	6,440
2014	281,155	9,267	204	6,728
2015	294,612	9,485	214	6,886
2016	296,673	9,333	215	6,776
2017	298,439	9,151	217	6,644
2018	299,188	8,954	217	6,501

[1]gigawatt-hour [2]kilowatt-hour [3]million tonnes of carbon dioxide

These numbers for electricity consumption and carbon footprint shown in Table 2-5 are a cause for concern in Saudi Arabia. Dasgupta and Chaudhuri (2020) cited the World Bank (2020) in reporting that based on the average electricity consumption levels in 2014, countries that have a higher income consumed approximately 8834 kWh per capita, whereas low- and middle-income countries consumed approximately 1922 kWh. Compared with Saudi Arabia in the same year (9267 kWh per capita), the country's consumption is 5% higher than that of higher-income countries and significantly higher (380%) than that of low- and middle-income countries. It is observed that there is a huge difference in the kWh per capita consumption of high-income and low- and middle-income countries, and this seems attributable to the level of improvements of the countries' electricity infrastructures and their industrial sector productivity (Azolibe and Okonkwo, 2020). [Note: regarding gross national income (GNI) of a country, high-income countries are those with a GNI higher than 9368.51£. Worldwide, 82 countries fall under this category, whilst the rest of the countries are under the low- and middle-income category. For more data about kWh per capita and GNI, see the World Development Indicators (World Bank, 2020)].

Historically, in comparison to other countries, Saudi Arabia has always provided cheap, government-subsidised energy (Mahmoud et al., 2017). The consequence of this has been that the true cost of energy and its environmental impacts have not been well recognised, and therefore, there has been a high net consumption per capita in the country. Table 2-6 outlines the old and the current tariff for domestic electricity. Even though Saudi Arabia increased the electricity tariff from (0.01- 0.060) to (0.036 - 0.060) £/kWh in 2018 (Saudi Electricity Company, 2018), there are two notable points:

1- The new electricity tariff price is considered not to cover the cost of electricity generation (Krarti et al., 2020; Poudineh et al., 2020); and
2- The new tariff is far below the average tariff in other countries (see Figure 2-5); for example, the average in European Union countries is 0.19 £/kWh (Europa, 2019) and in the United States is 0.11 £/kWh (EIA, 2020).

Table 2-6 Old and new domestic electricity tariffs in Saudi Arabia

Before 01/01/2018 (old tariff)		After 01/01/2018 (current tariff)	
Electricity consumption (kWh)	Price (£)	Electricity consumption (kWh)	Price (£)
0 - 2000	0.01	0 - 6000	0.036
2001 - 4000	0.02	More than 6000	0.060
4001- 6000	0.04		
More than 6000	0.060		

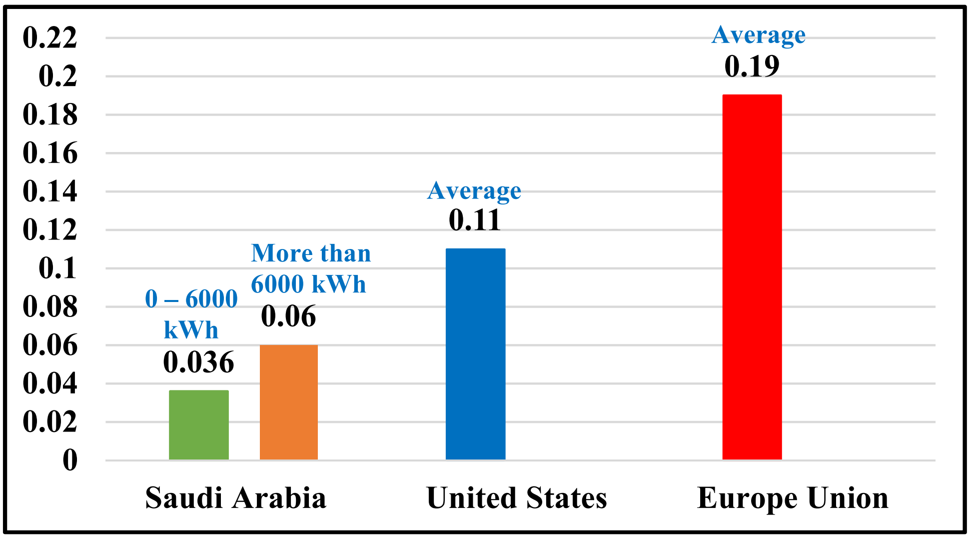


Figure 2-5 Different electricity tariffs (£/kWh) in some countries

In terms of how sectors in the country consume energy, Table 2-7 shows the Saudi Arabian energy consumption between 2010 and 2018 divided by different sectors, namely, residential, commercial, governmental, industrial, and others (General Authority for Statistics, 2018a). As a recent example, in 2018, the residential sector consumed 43% of the total energy consumption in the country; this is equal to 130,428 out of 299,188 GWh. Although the consumption of this sector dropped from 48% in 2017 (which could be attributed to the 2018 electricity tariff increase; see Table 2-6), it is still not enough. The Saudi Arabian residential sector's total energy consumption of 43% in 2018 was high compared to the energy consumption rates of residential sectors elsewhere at around the same time. The worldwide average was 27% in 2015 (International Energy Agency, 2019), the United Kingdom's average was 29% in 2018 (Department for Business, Energy & Industrial Strategy, 2019), Germany's average was 25% in 2017 (Grealis et al., 2019), and India's average was 9.14% in 2018-2019 (MOSPI, 2020). Moreover, the Saudi Arabian residential sector is the single highest consumer among other sectors in the country.

Table 2-7 Consumption of electrical energy by sectors between 2010 and 2018 (General Authority for Statistics, 2018a)

Year	Sector	Residential	Commercial	Governmental	Industrial	Others[1]	Total[2]
2010	GWh	109021	28918	28753	43247	8315	218254
	%	50	13	13	20	4	100
2011	GWh	109623	32622	27746	46726	8791	225509
	%	49	14	12	21	4	100
2012	GWh	120652	39388	30614	46626	9330	246610
	%	49	16	12	19	4	100
2013	GWh	126113	38882	32126	55636	9928	262685
	%	48	15	12	21	4	100
2014	GWh	136368	42274	35940	56618	9955	281155
	%	49	15	13	20	4	100
2015	GWh	144513	47163	39674	51856	11406	294612
	%	49	16	13	18	4	100
2016	GWh	143660	48225	38498	53587	12702	296673
	%	48	16	13	18	4	100
2017	GWh	143473	48349	38666	54863	13089	298439
	%	48	16	13	18	4	100
2018	GWh	130428	46849	43909	58177	19824	299188
	%	43	16	15	19	7	100

[1] Others: includes desalination, agricultural and other categories.
[2] Transport is not included in these electrical energy data. This is most likely because the transport sector in Saudi Arabia relies on fossil fuel sources, such as diesel and gasoline (Alshehry and Belloumi, 2017).

The construction industry is the leading revenue generator in the Saudi Arabian economy (El Mallakh, 2015). The construction industry's GDP has increased by around 3.8 times during the last two decades; see Figure 2-6. As a result, it consumes the highest percentage of energy and natural resources, making it a prime contributor to the country's carbon footprint (Opoku and Abdul-Muhmin, 2010; Alrashed and Asif, 2012b; Mansour et al., 2020).

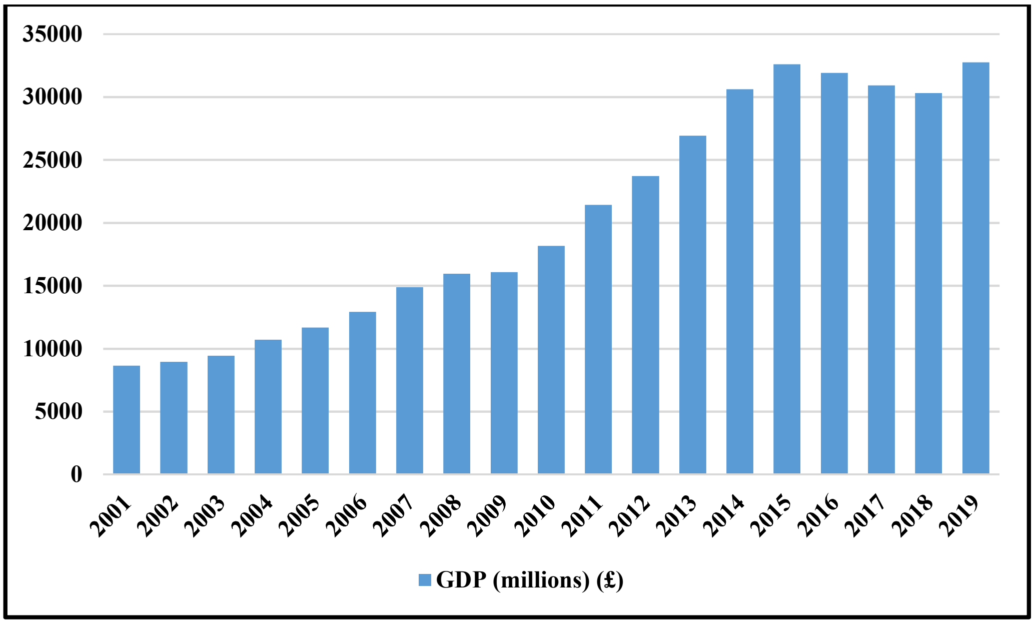


Figure 2-6 GDP for the construction sector by millions (£) (General Authority for Statistics, 2019a)

Table 2-8 shows the General Authority for Statistics' (2019b) data on the percentage of housing units (occupied by Saudi Arabian citizens) in 2019, categorised based on the building materials used in Saudi Arabian administrative areas (Saudi Arabia is divided into 13 administrative areas). In general, the main material used to construct housing units is concrete (89.45% of the housing units), followed by block/brick (10.44% of the housing units). There are two notable points. First, the lowest percentage of housing units built with concrete is found in the Hail and Jazan administrative areas, at 74.27% and 65.47%, respectively; second, Jazan is the only administrative area that has housing units built with stone (0.24%) (see Section 2.3.1 for more information about the construction materials used in Saudi Arabia).

Table 2-8 Percentage of housing units (occupied by Saudi Arabian citizens in 2019) in Saudi Arabia based on the building materials used (General Authority for Statistics, 2019b)

Administrative Area (Region)	Concrete %	Block/Brick %	Stone %
Al-Riyadh	98.67	1.33	0.00
Makkah	86.13	13.87	0.00
Al-Madinah	84.77	15.23	0.00
Al-Qaseem	91.00	9.00	0.00
Eastern Region	94.08	5.92	0.00
Aseer	88.13	11.87	0.00
Tabouk	91.48	8.52	0.00
Hail	74.27	25.73	0.00
Northern Borders	100.00	0.00	0.00
Jazan	65.47	34.28	0.24
Najran	83.00	17.00	0.00
Al-Baha	92.84	7.16	0.00
Al-Jouf	98.31	1.69	0.00
Saudi Arabia[1]	**89.45**	**10.44**	**0.02**

[1] This is not an average percentage. It is based on the total number of housing units in the country.

It was estimated that the country's population in 2019 was 34,218,169 (General Authority for Statistics, 2019c); however, the population is expected to increase by 2.52% annually (General Authority for Statistics, 2017a; Alqahtany, 2020). This means that in 2025, the population will be 39,729,066. Figure 2-7 shows the population for between 2014 and 2025; notably, in this period, the population will increase by around 31%. The exponential rise in Saudi Arabia's population has put pressure on the country to rapidly expand its modern housing supply, which has had a detrimental effect on national resources, such as energy and materials (Alrashed and Asif, 2012b; Al Surf et al., 2014; Alqahtany and Mohanna, 2019). For example, 209,566 and 215,594 new houses were built in 2017 and 2018, respectively (General Authority for Statistics, 2017b; 2018b). Similarly, in 2018, 28% of the total value of completed construction projects was spent in the residential sector, see Table 2-9 from the General Authority for Statistics (2018d).

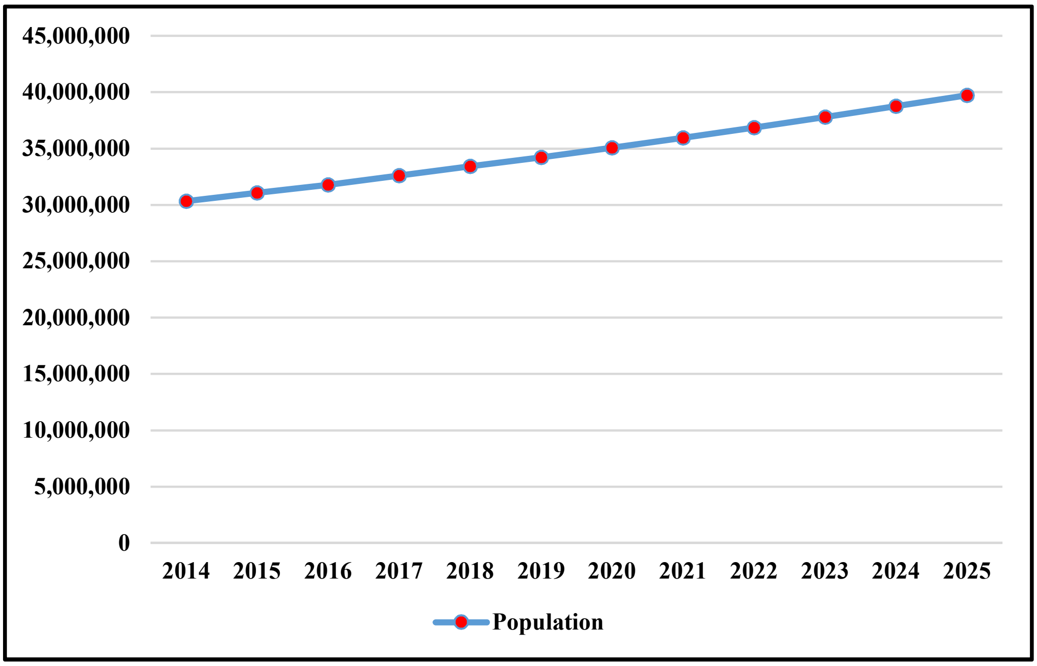


Figure 2-7 Saudi Arabia population (General Authority for Statistics, 2017a; 2018c; 2019c)

Table 2-9 Completed construction projects value (£) in 2018 (General Authority for Statistics, 2018d)

Projects type	Civil engineering construction (infrastructure)	Non-residential buildings	Residential buildings	All types
Total (£)	26,030,050,400	18,656,097,600	17,626,525,800	62,312,673,800
%	42	30	28	100

Therefore, there is a need for the government to introduce policies to promote the development of non-fossil-fuel sources of electricity as well as to reduce the usage of energy. Almutairi et al. (2015) recommended that the government introduce energy-efficient systems that permit citizens to enjoy the same level/quality of living but that reduce the net demand for energy and, thus, Saudi Arabia's carbon footprint. Therefore, quick wins and addressing the low hanging fruit is also a main focus of the country. Energy efficiency and material choices are key areas of this process.

Mahmoud et al. (2017) reported that the country is now addressing this high energy consumption by introducing more energy efficient and sustainable strategies, with particular focus on minimising the heavy environmental costs resulting from the construction industry. The country also has the ambitious *Saudi Vision 2030*, with an important goal of reducing its overdependence on oil as its energy supply by 2030—a vision that implements both sustainability and resilience measures (Government of Saudi Arabia, 2016). Gelil et al. (2017) viewed it as a step towards achieving the country's aim to reduce greenhouse gases and use its resources to expand the economy while reducing its carbon footprint. Areas of this vision that focus on resilience and sustainability will be outlined in Section 2.5; in particular, one of the initiatives for this vision was introduced in 2018, at the High Level Political Forum in the United Nations (UN, 2018).

The efficacy of existing tools for assessing sustainability and resilience in buildings is questionable regarding their applicability in Saudi Arabia (Shaawat and Jamil, 2014; Al-Tamimi, 2017) (see Section 2.5). Studies have shown that a system that is appropriate in one country may not work in another because of the local factors involved (Mortada, 2016; Alshuwaikhat and Mohammed, 2017; Alyami, 2019), for example, systems and materials used in construction, how resources are consumed, and how buildings should be built to meet local cultural and environmental requirements (Attia, 2013) (see a full list in Section 1.1).

2.3. Sustainability in the Saudi Arabian context

One of the aims of Saudi Arabia is to uphold its current position as one of the leading countries with regard to construction in the Arabian Gulf, both in terms of constructing iconic edifices (Aldossary et al., 2014c) and maintaining the ecological balance of the arid desert by minimising the consumption of water and energy resources (Abubakar and Dano, 2020). Saudi Arabia's construction industry is still in its infancy and, for all intents and purposes, can be considered to be still under development (Banani et al., 2016). This means there is flexibility to make changes, and this is the most convenient time to put into place regulations that foster and readily embrace sustainability. Al Surf (2017) advocated laws and regulations that would make their usage mandatory. These regulations should be implemented even though the construction industry is starting to grow at a remarkable rate (Sarhan et al., 2017; Shaawat et al., 2018); see Figure 2-6 in Section 2.2 for the GDP construction industry growth.

There are difficulties to be faced in implementing sustainability in Saudi Arabia (Al-Tamimi et al., 2017), particularly stakeholders (construction industry community). A study by Almahmoud and Doloi (2015) recommended that in Saudi Arabia, maintaining the stakeholders' satisfaction is a vital step to sustainability implementation. Challenges in Saudi Arabia's sustainability implementation can be surmised by reviewing surveys conducted in Saudi Arabia (Alrashed and Asif, 2012a; Shaawat et al., 2018). Firstly, Alrashed and Asif (2012a) investigated the opinions of non-government construction industrial representatives, such as engineers and contractors (122 participants), with respect to housing construction projects. When participants were asked about their priority among these factors [sustainability, construction time, safety, quality, architectural outfit and cost], they found that the cost featured as the main priority, as expressed by over a third of the professionals questioned, whereas only 2.5% of the professionals questioned considered sustainability as a main priority among other factors. Moreover, Shaawat et al. (2018) conducted a similar survey with 34 participants from the construction industry to determine where within each of the three pillars of sustainability [environment, economic and society] the most prominent barriers existed; the economy was chosen as the most significant barrier, and the lack of strong government support was reported as the central issue of concern over economics. The shortage of specialists to implement technological developments was the main issue concerning the environment pillar, and stakeholders' interest was seen as a possible problem in the social context.

Al-Torkistani et al. (2015) stressed the need to promote environmental investment by providing financial and non-financial incentives in Saudi Arabia that will encourage sustainable growth and future development. Thus, there is a need to create awareness among local communities to better inform them about the importance of developing sustainable buildings. Informing locals about the concept of sustainability providing healthier, more affordable, and better urban development, which is also environmentally sound, has been a major government undertaking (Al Surf and Mostafa, 2017).

In general, in order to enhance sustainability (i.e., utilise short- and long-term resources in a workable and cost-effective way), Ding (2014) suggested that building projects within Saudi Arabia and elsewhere around the globe must:

- Use as little energy as possible;
- Allocate resources responsibly;
- Use construction materials that have a low level of embodied energy; and
- Recycle and refashion material whenever possible.

All these suggestions by Ding (2014), along with designing cultural and natural resources to accommodate the requirements of global, regional, and local conditions, need to be reflected in the drawing up of new designs [a cultural resource refers to an object of significance to a group of people traditionally associated within it] (Matar, 2016). Such cultural requirements are reflected in the Saudi Arabian cultural design of residential buildings, for example. Given that Saudi Arabian families are large and close-knit, and their social norms involve close association with extended relatives and friends in the community, Alyami et al. (2013), for example, noted that for such family arrangements, domestic buildings should be able to accommodate populous social events. This means they can be large, which might of itself be suggested as unsustainable from a material consumption/cooling requirement point of view (see Section 5.5.1.2).

In the next sections, construction materials and energy will be reviewed in the context of Saudi Arabia, with more attention on domestic buildings.

2.3.1. Construction materials

The Saudi Arabian construction industry, and the nation as a whole, needs to lend support to the adoption of more sustainable building materials, including cognisance of the natural resources from which they are made and sustainable construction methods if true sustainability is to be achieved (Salam et al., 2014). Essential materials for manufacturing industries and economies can be both scarce and have high economic importance (Gardner and Colwill, 2016); this is as true in Saudi Arabia as anywhere else. For example, renewable energy technologies use some high-cost materials, including rare earth metals, such as neodymium and dysprosium (Fisher et al., 2012)—

hence, what is considered a sustainable/renewable technology now is highly dependent on a dwindling resource supply. Whilst Gardner and Colwill's (2016) research relates to EU member states, their findings are just as applicable to Saudi Arabia, where the need for establishing and developing sustainable manufacturing systems for the building industry is vitally important.

The most pressing challenge in the construction sector is the process of selecting the right building materials—in other words, those that are fit-for-purpose and those which fully embrace sustainability—because the use of the wrong construction materials hinders the possibility of advancing construction projects, which can cause significant setbacks (Kanniyapan et al., 2019). This is a philosophy upheld by Bakhoum and Brown (2012) and Jalaei and Jrade (2015), who suggested that all construction materials must be sustainable and resilient (see Section 2.4) and have a minimum impact on the environment whilst demonstrating their suitability to the task at hand, which is a complicated factor to measure. Although in the past, building materials have not been viewed as important in terms of environmental emissions, more focus is currently being placed on this and other areas, as the window of opportunity for action is narrowing (Vilcekova et al., 2018). Furthermore, calculating the impact on the environment of building materials has been found to be difficult because it depends on availability of data and assessment performed (for example, life cycle assessment (LCA) see Section 2.5.1.1), and queries have been raised regarding the accuracy of tools used to measure the impact (Emami et al., 2019).

Only one study (see Section 2.6) has considered the environmental impacts of materials in Saudi Arabia, for example, the embodied carbon and energy of construction materials in Saudi Arabian buildings using LCA. Asif et al. (2017) performed an LCA assessment (cradle-to-gate) using an existing small house (367.3 m^2 - three bedrooms) built in 2013 and located in Eastern province. The main outcome of this study is the role of the structural materials [specifically, concrete and steel], and in particular their environmental effects; see Figure 2-8 for the results of embodied energy. However, there were shortcomings in Asif et al.'s (2017) study:

- This study did not perform an analysis to reduce the carbon and energy embodied impacts of materials. In short, it did not suggest specific replacement materials as possible solutions for the exit situation; and
- It would be more beneficial if the selected house had been at the design stage. Achieving a high positive impact with more sustainable construction is influenced greatly by the overall design and, ultimately, by decisions taken at the early stages of the overall decision-making process (Cuéllar-Franca and Azapagic, 2012; Nielsen et al., 2016; Hasik et al., 2019).

However, in respect to the choice of materials for sustainable housebuilding, Asif et al. (2017) recommended additional research in Saudi Arabia to ascertain and test a much greater range of materials that are potentially far more beneficial and have less impact on the environment. There is also an urgent need to look at improving concrete material in Saudi Arabia, simply because of its environmental effects, as concluded by Asif et al. (2017) and the data reported by the General Authority for Statistics (2019b), which stated that around 90% of the housing units in 2018 and 2019 in Saudi Arabia (occupied by Saudi Arabian citizens) were built using concrete materials; see Figure 2-9. The effects of cement production are a global issue; 7% of the industry energy usage in the world is by cement production (ranked third among other industry sectors in terms of energy usage and second in terms of carbon footprint emissions) (International Energy Agency, 2018). Lupíšek et al. (2015) stated that materials that have been used for many years could be replaced by innovative and/or reusable materials to have less of an effect on the environment, whereas optimising building design and lessening the need for maintenance could also help to achieve sustainability.

Proposing alternative materials to reduce the embodied impacts (carbon and energy) in the design stage is where this study (RESAF) addresses the shortcomings in Asif et al.'s (2017) research. In addition to that, within this selection process of materials a procedure is needed to reduce pollution (carbon footprint) through the transportation of goods, and this involves project developers making use of locally available materials (Vukotic et al., 2010) in a country like Saudi Arabia. Several materials used in construction are manufactured within Saudi Arabia, such as cement products, insulation products, steel, block, aluminium and glass (Taleb and Sharples, 2011; Albelwi et al., 2017). Moreover, the environmental effects of buildings also do not stop at the embodied impacts of materials and their transportation; environmental effects covers more than that. For example, it plays a significant role in the building operation stage; this where the use of energy is involved—see Section 2.3.2.

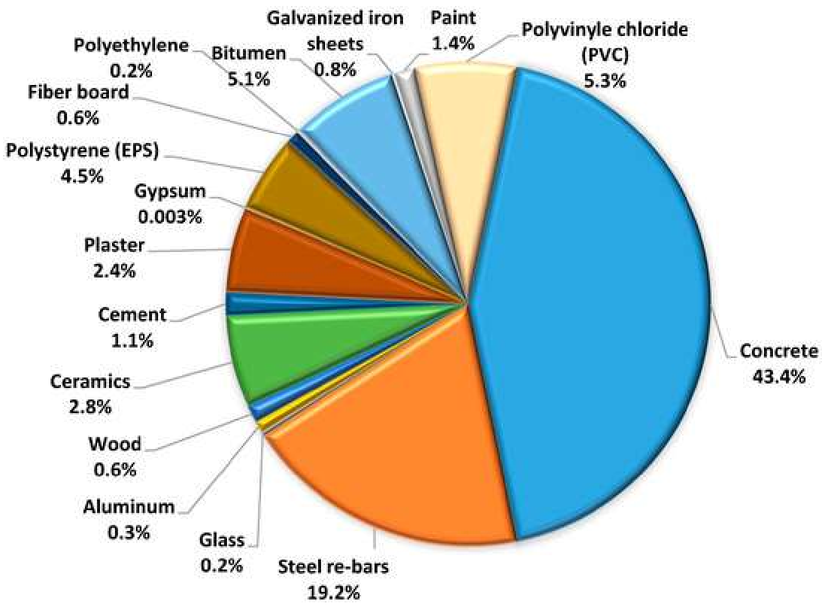


Figure 2-8 Embodied energy (MJ) for construction materials – house (Asif et al., 2017)

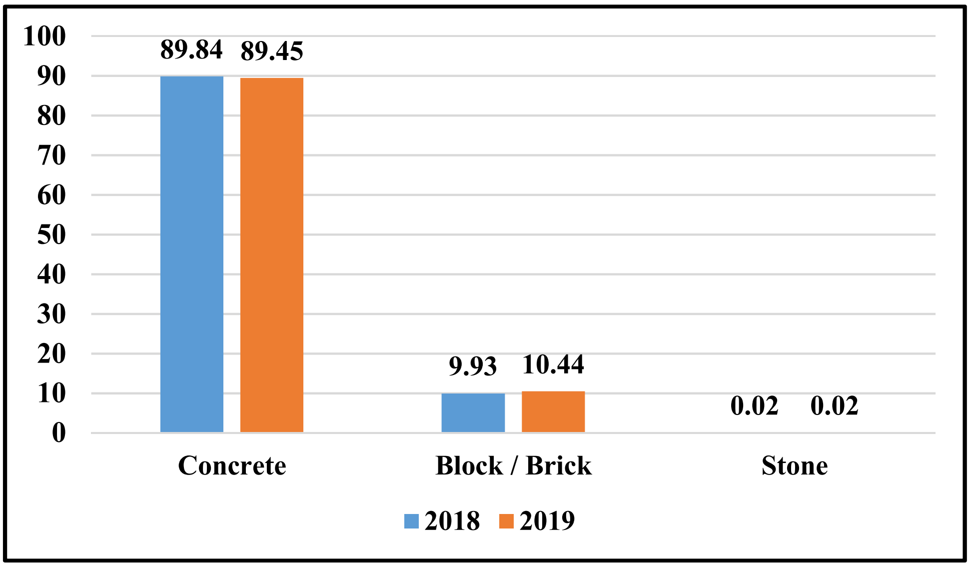


Figure 2-9 Percentage (%) of housing unit categorisation (occupied by Saudi Arabian citizens) in 2018 and 2019 based on the main construction materials used in Saudi Arabia (General Authority for Statistics, 2019b)

According to Khatib et al. (2019), the context of Saudi Arabia reinforces the need to plan project resources before embarking upon the construction phase; once this stage is reached, the opportunity to change material choices has effectively been removed.

However, that does not mean that the opportunity to minimise environmental impacts has been removed, for example, minimising the amount of construction waste produced, not least from domestic construction settings. Studies by Ouda et al. (2018) and Blaisi (2019) recognise the need to control construction on-site (including housing projects) pollution and the management of waste in Saudi Arabia; they advocate moving towards the recycling of materials for use in new construction and infrastructure projects. For example, the Construction and Demolition (C&D) scheme in Saudi Arabia, proposed by Ouda et al. (2018)—see Figure 2-10 for more information—includes potential recycled materials (i.e., bricks and rock) and possible applications (i.e., backfill) along with limitations (i.e., lack of standards and costs) and tips for successful applications (i.e., promoting the market of recycling materials). Therefore, Saudi Arabia needs to build more waste management recycling facilities and upgrade those already in existence.

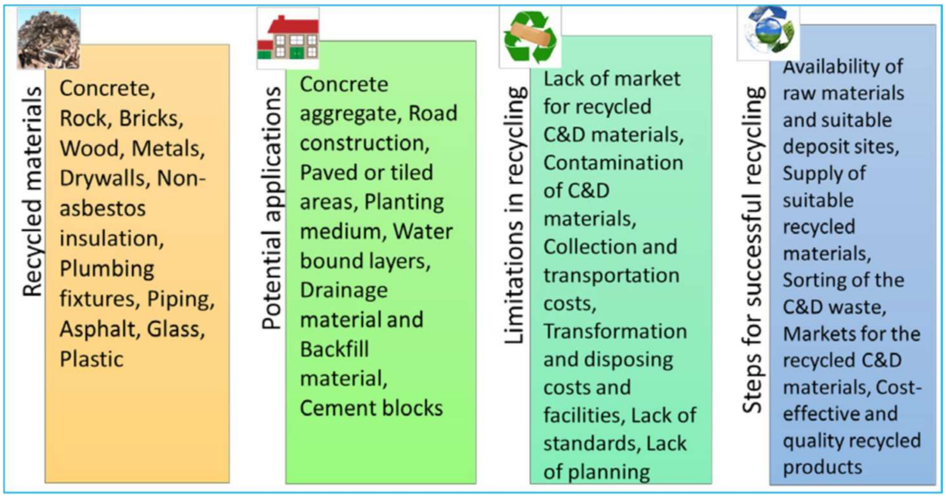


Figure 2-10 Plan of construction and demolition waste (Ouda et al., 2018)

2.3.2. Energy use in the 'domestic' building sector

2.3.2.1. Current energy consumption

The huge energy consumption in Saudi Arabia has been attributed primarily to the residential sector (Al Kanani et al., 2017), which has the highest national electrical demand amongst all sectors in the country (43% in 2018) (see the latest released official records by the General Authority for Statistics (2018a) in Table 2-7 – Section 2.2). Therefore, the topic of energy use of residential buildings has been studied several times within the literature; see Section 2.6.

Krarti et al. (2020) stated that energy use intensity (EUI) for Saudi Arabian residential buildings in 2017 is up to 182 kWh/m^2 (EUI is calculated based on the total consumed energy for all domestic buildings in the country divided by the total area of all domestic buildings in the country). Alrashed and Asif (2014b) also scrutinised the figures of electricity use in 115 houses in the city of Dhahran, Saudi Arabia. The average figure over a 12-month period was 176.5 kWh/m^2. Other studies suggested even higher figures; for example, Alaidroos and Krarti (2015b) found that a house in the cities of Dhahran and Riyadh, Saudi Arabia, consumes more than 228 kWh/m^2 annually. All these figures of electricity consumption are on the high side when set against global averages for existing houses. For example, in the Southern part (hot-humid climate) of the United States, a house consumes 130 kWh/m^2 annually (Alrashed and Asif, 2014b), and in the United Kingdom, the figure was 88–125 kWh/m^2 in 2017 (Department for Business, Energy & Industrial Strategy, 2019).

The domestic target figure in Saudi Arabia to achieve a reduced use of energy is around (77 to 98) kWh/m^2 annually, which was proposed by Aldossary et al. (2017) based on a low carbon houses framework (see Section 2.5.2.5 for more details about the framework). Table 2-10 presents definitions of low carbon houses from a number of different countries. The differences between them clearly show that different nations have different views about what constitutes low energy consumption (Aldossary et al., 2017).

Table 2-10 Several countries' definitions of 'low carbon' houses extended by researcher based on Aldossary et al. (2017) modified from Thomsen and Wittchen (2008)

Country	Official definition
Austria	• In order for heating systems to be classed as low energy, their energy consumption must be less than 60 to 40 kWh/m^2 per year. • A house is classed as passive if energy consumption is 15 kWh/m^2 per useful area (Styria) and per heated area (Tyrol).
Belgium (Flanders)	• Low energy houses consume 40% less than standard houses. • Very low energy houses consume 60% less energy.
Czech Republic	• Low energy houses consume between 51 and 97 kWh/m^2 per year. • Very low energy houses consume 51 kWh/m^2 per year. • The standard of a passive house is 15 kWh/m^2 per year.
Denmark	• A house qualifies for class 1 low energy if its energy consumption is less than 50% of the minimum requirement for new houses. • A house qualifies for class 2 low energy if its energy consumption is 25% lower than the minimum requirement for new houses.

Finland	• Low energy houses have to consume 40% less energy than standard houses.
France	• New houses: consumption of energy per year (for air conditioning, heating, lighting, and hot water) must be less than 50 kWh/m^2 (or 40 to 65 kWh/m^2, depending on climate. • Existing houses: consumption of energy per year (for air conditioning, heating, lighting and hot water) must be 50% lower than that stipulated for new houses. • For renovations: from 2009 onwards, consumption of energy per year must be 80 kWh/m^2.
Germany	• Normal house consumes (60 kWh/m^2 or 40 kWh/m^2) per year. • Passive house consumes less than (120 kWh/m^2) per year. A condition heating demand not exceed 15 kWh/m^2.

2.3.2.2. Reasons of high energy demand

The core problem with housing development in Saudi Arabia relates to the poor design, leading to low resistance and high emittance in terms of heat/cold, because these design flaws result in the uninhibited transfer of heat from outside to inside, which requires the high usage of air conditioners with their attendant high energy consumption (Choguill, 2008; Taleb and Sharples, 2011; Esmaeil et al., 2019). According to Abd-ur-Rehman et al. (2018), most building designs, even those built in the last ten years, in Saudi Arabia do not take into account sufficiently energy savings through good building design and material choice options. A software named DesignBuilder has been deployed by Taleb and Sharples (2011) to simulate possible energy consumption (higher demand) problems of existing residential buildings (apartment complexes) with current design standards in the Saudi Arabian city of Jeddah and found the following:

1. Inadequate climate-responsive design principles;
2. Insufficient insulation in both roofs and walls. This is supported by a recent data bulletin published by General Authority for Statistics (2019d), which stated that in Saudi Arabia, 57% of houses do not have insulation, around 23% of houses are insulated, and regarding the rest of houses, it is not known whether they are insulated or not (see Figure 2-11);
3. Low-quality window glazing; and
4. Insufficient use of recycled or sustainably sourced building materials (Section 2.3.1)

All of these factors result in a waste of 32% of energy resources. Several other studies (such as Alaidroos and Krarti, 2015b; Mujeebu and Alshamrani, 2016; Al Surf, 2017; Ahmed et al., 2019; Alshahrani and Boait, 2019; Esmaeil et al., 2019; Felimban et al., 2019; Al-Saggaf et al., 2020; Krarti, 2020; Krarti and Howarth, 2020) raised these issues, and they added the following:

1. The role of air conditioning (AC) in buildings (Aldossary et al., 2015a Mujeebu and Alshamrani, 2016; Felimban et al., 2019; Almasri et al., 2020; Krarti and Howarth, 2020); in Saudi Arabia, cooling accounts for around 66% of the electricity demand for the domestic building (see Section 1.1 – Figure 1-1). That is why cooling and heating of the building is the factor used by RESAF during the in-use stage (see Section 3.2.1 – Figure 3-2);
2. Current low tariffs for electricity (see Figure 2-5 and Table 2-6 in Section 2.2);
3. Occupant behaviour, for example, AC thermostat (room temperature) control and using AC for a long time (Alshahrani and Boait, 2019; Felimban et al., 2019); and
4. Domestic building designer issues, for example, lacking professional experience and being unaware if there are building codes in the country (Ahmed et al., 2019).

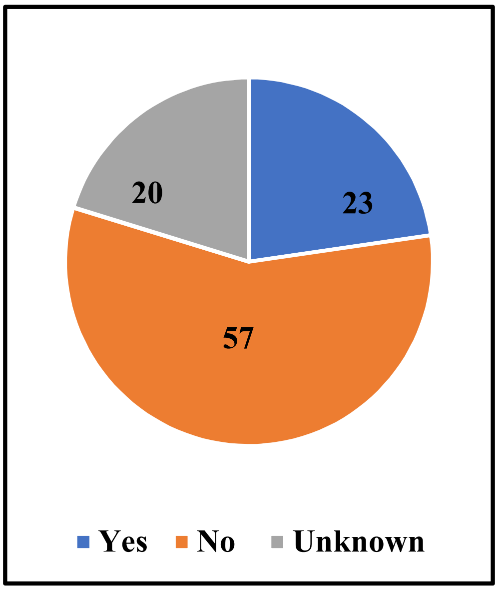


Figure 2-11 Percentage of housing units that use thermal insulation in Saudi Arabia (General Authority for Statistics, 2019d)

2.3.2.3. Solutions for high energy demand

A number of studies have proposed solutions for the higher demands of energy in the country. For example, studies have utilised the software called IES Virtual Environment (IES-VE) for energy consumption modelling of residential buildings in two separate Saudi Arabian cities, namely, Jeddah and Riyadh. Potential solutions for energy overuse have been proposed (Aldossary et al., 2014a; 2014b):

1. Finding new methods of creating the right sort of building fabric, such as selecting efficient insulation or window type;
2. Deploying alternative energy sources (i.e., wind or solar energy) that yield sufficient output; plus
3. A variety of architectural innovations, such as landscaping and incorporating shading devices.

Other studies support these ideas to improve the energy demand of domestic buildings, such as building envelope design (i.e., reduce window ratio in the building facade and using shading when using windows) (Ghabra et al., 2017), using thermal insulation in walls and roofs (Al Kanani et al., 2017; Alghamdi, 2019; Alaboud and Gadi, 2020), and using air conditioner with low electricity consumption (see Figure 2-20 in Section 2.5.2.1 for an example of air conditioner labelling-based information about energy efficiency) (Matar, 2016; Howarth et al., 2020).

Proposals of frameworks and models have been established to reduce the demand for energy in the residential sector: firstly, a low carbon housing framework (Aldossary et al., 2015a; Aldossary, 2015), and secondly, a model proposed by Al Surf (2014; 2017) for sustainability development in housing, which considers energy along with other aspects—please refer to Sections 2.5.2.5 and 2.5.2.6 for specific details about these frameworks.

Hence, a range of options must be considered to ameliorate the negative effects from energy consumption. The positive impact that a thriving construction industry has on the economy must be balanced with the negative effects on the environment (Mahmoud et al., 2017). Other researchers have proposed using green roofs to reduce the energy consumption of residential buildings (Khan and Asif, 2017; Mahmoud et al., 2017; Khabaz, 2018). However, in a country like Saudi Arabia, whilst green roof buildings would be a change in building material and could create a positive role in community service, the maintenance (including watering) would need to be considered (Khabaz, 2018), so the efficacy of a green roof might be challenged by other effects, such as water and hot weather in the country.

Additionally, whilst not a focus of this study, Mujeebu and Alshamrani (2015), Abd-ur-Rehman and Shakir (2016) and Abd-ur-Rehman et al. (2018) have shown that solar energy has significant potential in the domestic sector. Given the high values of irradiance and sunshine hrs (circa 9 hrs/day) this can be viewed as a sustainable option for Saudi Arabia (Rehman, 1998; Almasoud and Gandayh, 2015). Concerning energy demand and its effect on the environment, the implementation of renewable energy technologies is viewed as the most long-lasting solution to most of the issues facing the country regarding environmental pollution. This argument is very much based on a sustainability perspective that provides a long-term realistic alternative to fossil-based alternatives such as oil. This is vitally important, as many suggest peak energy demand will be reached in 2032 (Abd-ur-Rehman et al., 2018).

Furthermore, the development of sustainable buildings (for example, used energy) is a contentious issue, as competition for sometimes limited resources can have a detrimental effect on the environment and on improving socio-economic issues related to sustainability (Rogers et al., 2017). As such, decision-making tools are of major importance, particularly in the renovation of existing buildings (Nielsen et al., 2016), as they help to establish sustainable targets for projects. The design process, as one of the decision-making tools, ensures sustainability standards are met in renovation programmes. This is true for Saudi Arabia, where 3,462,755 traditional domestic buildings were occupied by Saudi citizens until the first half of 2019 (General Authority for Statistics, 2019b); for the ages of these buildings, see Figure 2-12. A study by Krarti et al. (2020) stated that the domestic sector could save around 50% of energy consumed and the same will apply to the carbon footprint, if optimal retrofit—based on, for example, the location (city) and type of building (i.e., flat/house)—has been applied to the existing domestic buildings. It proposed that changes be made to existing buildings, so energy consumption will improve; the changes are as follows:

- Add wall insulation;

- Replace windows;
- Add shading devices to the windows;
- Increase the temperature thermostat (by 1 or 2 °C) when using the air conditioning (AC). Most domestic buildings in Saudi Arabia currently use the typical setting (18°C) for AC temperature thermostat (Krarti and Howarth, 2020); and
- Use higher energy performance appliances; for example, another study by Krarti and Howarth (2020) proposed a solution to use high efficiency AC equipment in instead of the existing AC. See Figure 2-20 in Section 2.5.2.1 for a sample of the energy efficiency label used for AC in Saudi Arabia.

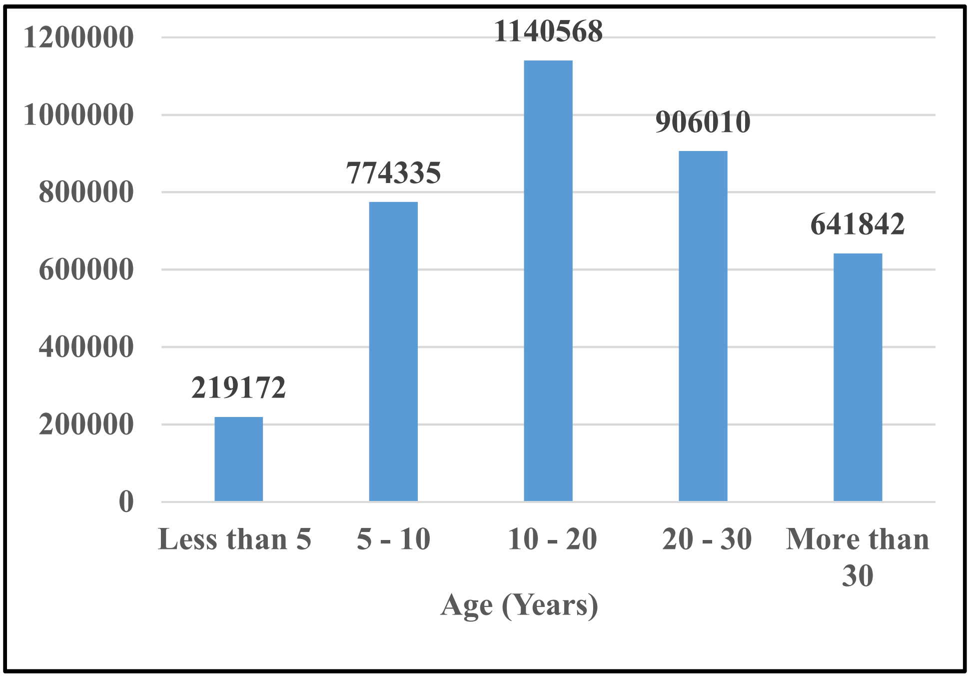


Figure 2-12 Domestic buildings' quantities categorised based on their age (years) (General Authority for Statistics, 2019b)

There are other ways to reduce the energy demand in domestic buildings, such as managing the electricity tariff in the country (Matar, 2018; Alaidroos and Krarti, 2015b); the government charges homeowners a discount electricity tariff in Saudi Arabia (see Section 2.2). The first study, by Matar (2018), focused on increasing the electricity tariff price, and the second, by Alaidroos and Krarti (2015b), focused on keeping the electricity tariff price at the same level without any increase, and proposed that the government invest in home energy efficiency. Matar (2018) concluded that if the tariff price changed (increased), this would reduce the energy demand for the houses with no energy efficient solution (i.e., no thermal insulation), because households would act to reduce their energy demand by, for example, raising the air conditioning thermostat. In contrast, households will not reduce the energy consumption if they live in houses with energy-efficient solutions. Prior to this, the second study by Alaidroos and Krarti (2015b) conducted a simulation analysis using software (EnergyPlus) on the energy use of similarly constructed domestic buildings in separate cities in Saudi Arabia and found that cost reductions could be achieved on annual subsidies. This study recommends that the Saudi Arabian government subsidise each house with around £5,519 to improve energy efficiency. This, in turn, will reduce energy consumption during the building's life. The argument here is based on the long-term use of the house (30 years):

- The homeowner will save on energy bills;
- The government would invest more than £5,519 [the government charges homeowner a discount electricity tariff (See Section 2.2)]; in return, it is expected that the initial investment will reduce subsidised energy cost by 54% in the long term; and
- These savings in government money can be invested in additional power stations. The reduced energy consumption will lower the demand for oil use (see Section 2.2 for issues regarding oil and electricity in Saudi Arabia).

From all of the previous sections, past studies have revealed many ways to reduce the energy demand from changing the building design features, solar energy solutions, and suggestions on electricity tariff changes or additional investment from the government. However, no study links the in-use energy demand (current section) with the environmental embodied impacts of construction materials (see Section 2.3.1) to achieve energy and carbon savings in both stages, which is what the current study RESAF focuses on.

2.4. Resilience in the Saudi Arabian context

Looking at the systematic literature review, a number of papers considered the resilience concept in Saudi Arabia; however, buildings including domestic type or construction materials are not considered (see Section 2.6). The available studies considered topics like *'community resilience to disaster'* (e.g., Alshehri et al., 2013a; 2013b; 2015a; 2015b) or the role of geographical information to identify future hazards (emergencies) (Abdalla and Alharbi, 2017). Thus, a country is vulnerable to many natural catastrophes, as recent events (i.e., floods, dust storms, or epidemics) have illustrated, and the nation lacks a management approach to such events (Alshehri et al., 2015a). So, these studies do provide suggestions for appropriate structures for implementing 'resilience' polices to help communities. These studies are not related to the current study (RESAF), although lessons may be learned in relation to the willingness and responsibility of people or governments to avoid repeating previous mistakes simply because they are not prepared for the disaster (Alshehri et al., 2015a; 2015b) due to poorly constructed infrastructures, which cannot deal with floods, windstorms and other disasters. In the context of RESAF, this is actually a drive for the construction industry to address the issues of energy and materials in domestic buildings (which has been raised in Section 2.3) by proposing solutions that can be maintained in the future.

In terms of energy consideration, because of the particular energy supply (i.e., oil), of which there has always been an abundance, applying environmental conditions incorporating energy-saving features within arid desert countries such as Saudi Arabia, while simultaneously trying to reduce relatively high carbon footprints (see Table 2-5 in Section 2.2), has previously been problematic (Alrashed et al., 2017; Krarti et al., 2017; Amran et al., 2020). However, there is now an understanding that reliance on these energy sources and the countries' primary wealth-producing vehicles cannot be guaranteed long term into the far future; this has a significant impact on Saudi Arabia's resilience (Taher and Hajjar, 2014; Alshibani and Alshamrani, 2017). It is now widely recognised by the Gulf Cooperation Council (GCC), which includes Saudi Arabia, that diversification is required in order to meet burgeoning domestic energy demands as a consequence of large increases in the population and in industry (Al-Saleh et al., 2012; Asif, 2016), (see Table 2-7 and Figure 2-7 in Section 2.2). According to Youssef and Hamid (2014), residential housing possibly presents the largest opportunities for implementing energy-saving practices, but as with any new venture, it will face many difficulties along the way, such as how any solutions will be promoted and disseminated in the future by builders or homeowners. This means domestic properties need a resilient practice (solutions) to overcome the energy problems, such as the solution being accepted by the public and by the construction industry (awareness) (Al Surf and Mostafa, 2017).

On other hand, regarding the types of materials used in construction (see Section 2.3.1), the most important work by the engineers will involve selecting the component parts that strengthen a building, providing its resilience to catastrophes, both natural ones and those resulting from human activity (Chaudhary and Piracha, 2013). In reality, resilience in materials offers more than future proofing of the building or what might be called the bounce back ability of the building:

- It can be extended to ensure the supply chain of the materials, for example, the materials are available and can be sourced (Jabbarzadeh et al., 2018). In Saudi Arabia, reinforced concrete is the main structure material for housing projects (Attia, 2013), when it is changed or modified, the alternative should be available;
- Balance should be achieved between the design requirements and future needs (Middleton, 2018). For example, in Saudi Arabia, builders construct using masonry blocks, as this method is flexible when there are future plans for modifications or additions to the building; and
- Environmental considerations should be taken into account in the future for selecting materials. In Saudi Arabia, reinforced concrete needs to be modified to have fewer carbon and energy embedded impacts (see Figure 2-8 – Section 2.3.1 for concrete's role in embodied energy for a building).

Moreover, local materials may be used in Saudi Arabian construction; designers should understand how historic buildings have been constructed (Susilawati and Al Surf, 2011). An example of the resilience of traditional building materials in the Saudi Arabian area has been highlighted by Mortada (2016) in a discussion about regional desert architecture. For example, historical records from the area of Najd, in the centre of Saudi Arabia, depict protrusions on walls and external parapets, which are designed to deflect raindrops away from the mud walls. The resilience of mud as a building material was illustrated dramatically in an 1817 battle at al-Rass in al-Qasiem in Najd: the mud walls were attacked but withstood 30,000 rounds of bullets and shells by the artillery of Egypt's Ibrahim Pasha over a three-month period.

Finally, this concept of resilient solutions is ground breaking in Saudi Arabia, and further extensive research needs to be conducted to ensure that the proposed solutions are indeed resilient (see Section 2.6 for the lack of available studies in the literature about buildings in the country), that they are guaranteed by law, and that builders, designers, and stakeholders will implement these innovations. This study will provide insight into important considerations for the proposed resilience solutions (selected materials), specifically in terms of uncertainty in the future, and how these solutions will perform. In short, a resilience filter will be the main element of RESAF (see Figure 3-2 in Section 3.2.1).

2.5. The concept of integrated sustainability and resilience in Saudi Arabia

The systematic review identified three papers and government documents that studied both sustainability and resilience in the Saudi Arabian context (see Figure 2-27 in Section 2.6). First, regarding Alshuwaikhat and Mohammed (2017), it mainly considered the sustainability of *Saudi Vision 2030*; however this paper gave brief indications about resilience; these indications were about not-for-profit organisations and their role was to be resilient through improving the regulations. This could be achieved, for example, by establishing endowments (for sustainable funding - by increasing the GDP contribution of these organisations from 1–5%), as when these organisations are strong, that will have a positive impact on supporting important sectors, such as education, healthcare, and housing. Two other papers are not related to the topic of this study: Ndubisi and Al-Shuridah (2019) is about organizational mindfulness (management strategy topic), and the second one, by Niyazi et al. (2019), is about monitoring groundwater resources, and their vulnerability to factors such as climate change or natural catastrophes. Some other references may include only the concept of sustainability; however, they will be used to support the argument of integrating sustainability and resilience later in this section.

Alongside *Saudi Vision 2030* (Government of Saudi Arabia), regarding their initiatives, in July 2018 in New York, at the High Level Political Forum, the Kingdom of Saudi Arabia highlighted its commitment to '*Transformation towards sustainable and resilient societies'* by presenting the first Voluntary National Review of progress toward the Sustainable Development Goals (SGDs) (UN, 2018). The following SDGs resonated with Saudi Arabia's objectives within the construction industry to create dwellings that are more resilient and sustainable:

- *SDG 7: Ensure access to affordable, reliable, sustainable, and modern energy for all;*
- *SDG 11: Make cities and human settlements inclusive, safe, resilient, and sustainable; and*
- *SDG 12: Ensure sustainable consumption and production patterns.*

Similar to many countries, the tools that Saudi Arabia has at its disposal to achieve this are somewhat disparate, and in order to initiate integral systems, it needs to observe the frameworks that are in place in countries for which these systems are standard practice, for example, in Western countries. However, there has to be consideration of the fact that the environment and the climate in Western countries are, of course, markedly different from in Saudi Arabia (Al-Gahtani et al., 2016). Regarding environmental evaluation systems, methods that are in place in other countries cannot be implemented universally because of the different materials used in construction projects, construction techniques, government policies, and citizens' attitudes (Alyami and Rezgui, 2012).

There has been much discussion from those within the construction industry about how applicable the current international assessment tools are for calculating building performance in desert countries like Saudi Arabia, not least because of factors such as geographical position, weather, economic strength, and national culture (Banani et al., 2016). According to Maslesa et al. (2018), there are two standard methods of assessment that can be used in the quantification of environmental building performance. The first employs tools that provide specific criteria for ranking buildings, for example, the Building Research Establishment Environment Assessment Method (BREEAM) or the Leadership in Energy and Environment Design (LEED). These methods include sustainability criteria that are credit-centred based on elements such as

- Adoption of the most suitable choice and use of site,
- Water conservation,
- Energy efficiency,
- Internal air quality,

- Use of recycled material, and
- General wellbeing.

However, whilst these US and British frameworks (i.e., LEED and BREEAM, respectively) are readily adopted in order to create buildings that are environmentally sustainable, these frameworks are still considered somewhat inappropriate by sections of the building industry (including housing projects), not least when it comes to assessing the resilience of the chosen materials (Attia, 2013; Al Surf, 2017). For the most part, this is somewhat remiss for various reasons; for example:

- The context and conditions of a country like Saudi Arabia, see Section 1.1 for the influential factors in Saudi Arabia (i.e., materials used in construction) (Attia, 2013) differs. Based on Al Surf's (2017) study, when a tool like LEED is applied in Saudi Arabia, the final construction project will not be '*fully sustainable'* because many sustainability indicators within a tool such as LEED are not designed specifically for the Saudi Arabian context and may be considered inapplicable or inappropriate, resulting in a construction project that may gain or lose unjustified points (Attia, 2013; Al Surf, 2017); see next point as an example;
- In some countries, like Saudi Arabia, it might be difficult to find materials that are locally available and that satisfy these frameworks due to the limitation of materials that get certified and the lack of experts (Ismaeel, 2019). Materials should be readily available to maintain the future demand for construction; and
- These frameworks should not use historical data; therefore, projections of data are recommended to assess future resilience regarding issues such as climate conditions as well as the quality of the construction system or materials (Champagne and Aktas, 2016; Marjaba and Chidiac, 2016).

Moreover, Shaawat and Jamil (2014) and Doan et al. (2017) found that both methods of rating were based on regional realities, not least when it comes to the choice of material. The selection of sustainable and resilient materials should include the resources and materials that exist in that region and the customs and traditions of the area. Therefore, a rating system that has been devised for one area should not be deployed unmodified in another, as otherwise inapplicable, inappropriate, and incorrect assessments/ accreditations will ensue. That said, the process of drawing from and refining measuring tools that are known and established can guide local practitioners in Saudi Arabia in the correct choice of sustainability indicators, metrics, and benchmarks. The main concern of the sustainability approach within construction has to be to reduce both solid waste and greenhouse emissions to avoid wasting natural resources whilst increasing environmental pollution. This is where the lifecycle assessment (LCA) comes into its own.

2.5.1. Internationally available tools and guides

A selection of popular current international environmental sustainability (ES) and resilience assessment (R) toolkits will be explored in Section 2.5.1. These include the following:

ES1. LCA – Life Cycle Assessment (2.5.1.1)

ES2. The Green Guide to Specification (2.5.1.2)

ES3. LEED – Leadership in Energy and Environment Design (2.5.1.3)

ES4. BREEAM – British Research Environmental Assessment Method (2.5.1.4)

R1. BRRT – The Building Resilience Rating Tool (2.5.1.5)

R2. Designing a Resilient Cities Guide (2.5.1.6.)

In Section 2.5.2, these are compared / contrasted to those toolkits that are locally derived and applicable to Saudi Arabia currently.

2.5.1.1. Life Cycle Assessment (LCA) in the 'domestic' building sector

To assess the environmental weight of services and goods over their entire useful life, an LCA (Ortiz et al., 2009) is commonly used. This method can help to perform overall conceptual assessments, or it can be used as an evaluation tool. As a tool, an LCA can determine what energy and basic materials are necessary to create products; it can also deduce what effect the by-products of production will have on natural elements, such as water, earth, and air. Conceptually, an LCA can be engaged to consider the products notionally, from conception to demise, to prioritise methods of devising solutions to problems (Bakhoum and Brown, 2013). According to ISO 14040 (2006), the LCA comprises four steps, as described in Table 2-11.

Table 2-11 LCA steps (ISO, 2006)

No	Steps	Description
1	Goal and scope definition	It outlines the LCA study boundaries and limitations. This includes but is not limited to, what the system is (i.e., type of building, materials), purpose of assessment, boundaries of the assessment (i.e., cradle to gate/site/grave), the functional unit (i.e., kg, MJ, and kgCO_2e).
2	Inventory analysis	It considers the inventory of input/output data, in short, collecting the data needed for the LCA study. For example, when the LCA study assesses a material, the quantity of this material and the data needed for calculations are collected.
3	Impact assessment	It produces the result of the LCA study in the format of values for each of the impacts. For example, when assessing a material, the result for measuring the embodied carbon impact is (i.e., 1 kgCO_2e) and the embodied energy impact is (i.e., 1 MJ).
4	Interpretation	It focuses on the results of the LCA study, so the results can be analysed for conclusions and recommendations.

Implementing the LCA in the field of construction is a complicated process, as there are many products involved in construction, and making inventories and assessments requires much preparatory work (Bribián et al., 2009; Soust-Verdaguer et al., 2016). It is also data intensive; an LCA needs a significant amount of information, particularly for analysing construction materials' embodied effects (Röck et al., 2018). Moreover, analyses may focus on different factors and have separate boundaries, ranges, methodologies, structures, inventories of data, and assumptions. Comparisons cannot always be easily made, nor can planners be sure of what, if any, degree of error there may be (Meneghelli, 2018). This explains, to some extent, why the LCA has not been implemented widely and why it is not a fundamental element of building regulations (Hernandez et al., 2019). Refer to Section 3.2.1.1 for a simplified life cycle assessment by Bribián et al. (2009) that would be appropriate for implementation in the field of construction.

There are numerous phases involved in building based on BSI (2017b):

- *'Product stage (A1-3)'*: the location and extraction of raw materials, which must be transformed, manufactured, packaged, and delivered to sites;
- *'Construction process stage (A4-5)'*: the process of building;
- *'Use stage (B1-7)'*: the control and upkeep of some buildings and the demolition of others; and
- '*Benefits and loads beyond the system boundary (D)'*: the recycling or disposal of waste products.

All these phases are illustrated in Figure 2-13 (Fantozzi et al., 2019). Every phase, shown as STEPS A-D, involves the use of a lot of energy and produces significant emissions of carbon dioxide gas (or its equivalent).

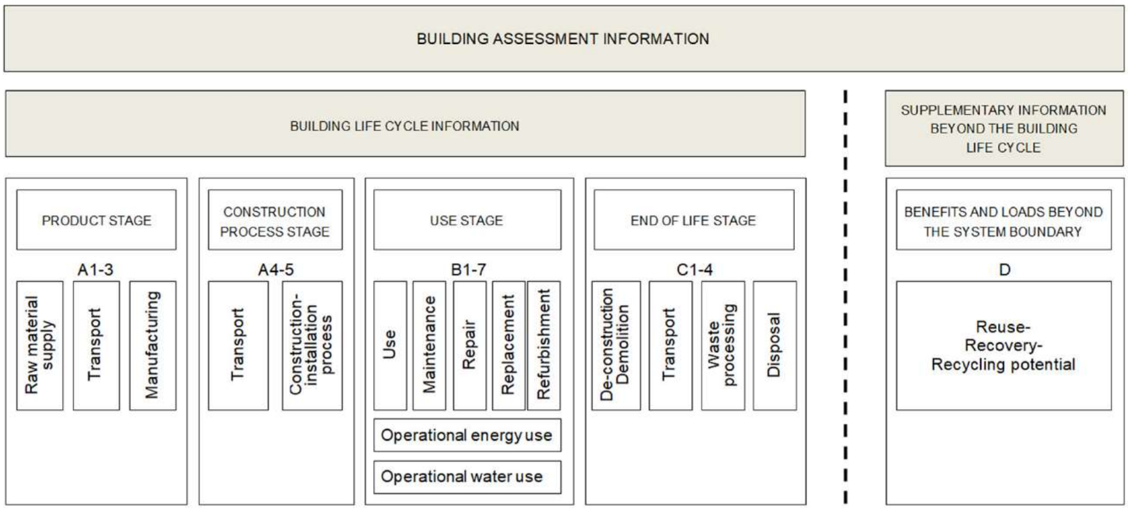


Figure 2-13 Building and construction material(s) lifecycles (Fantozzi et al., 2019)

Blengini and Di Carlo (2010) classified two principal LCA factors in construction. The first is the material LCA, which analyses the environmental effects of the materials used—see A1-3 (product phase) in Figure 2-13—while the second is the overall building LCA, which assesses the entire environmental consequences during the whole life of the building—see A to D (product phase to recycling phase) in Figure 2-13. For instance, if there is a building design, the first type will assess just the construction materials (i.e., concrete and steel), while the second type will assess all the phases, such as the construction materials and other related phases, such as use of the building (operation), demolition, and reuse of materials.

The construction of a building is dependent on several elements, such as the following (Asif et al., 2017):

- the design of the building;
- the type of construction material(s) used;
- the purpose (end-use) of the building;
- the estimated building lifespan; as well as
- the climatic conditions of the building site.

In this case, the LCA's main role is to help the building planners to correctly assess the total amount of construction material and energy required. An LCA also conducts an evaluation assessment to identify the possible adverse effects of the construction on the environment, such as carbon emissions, eutrophication, oxygen depletion, and acidification of land and water (Finkbeiner et al., 2006; Finnveden et al., 2009; Colangelo et al., 2018).

Sustainable building practice within the domestic sector is very much dependent on the client/designer - architect/contractor/builders all choosing the right type(s) of materials; if they are sustainable, the development has a greatly improved chance of being so as well. To achieve this, materials should be sustainable throughout their entire useful life (Bakhoum and Brown, 2012). This includes selecting materials with low levels of embodied carbon and increasing the materials' efficiency when used for construction (De Wolf et al., 2015). An example of material efficiency is reducing the waste of materials in the construction process. The use of an LCA helps to further protect the environment by considering the range of products available and offering detailed assessments on the potential environmental effects of certain products, thereby allowing stakeholders to be informed about their decision-making (Petrovic et al., 2019).

Professionals deploying an LCA as a tool to assist with decision making must work collaboratively to raise the level of transparency and reliability of LCA inputs and outcomes (Speck et al., 2016). De Wolf et al. (2017b) found that, at present, large amounts of academic input into industrial practice have yet to be implemented in construction projects. Similarly, reliable data-driven assessments of embodied energy and carbon are still applied widely in the construction industry; the assessor's assumptions and flexible boundaries result in a considerable variation of results, so to date, there are not enough data with which to set meaningful benchmarks. There are two sources of building inventory data (Anand and Amor, 2017):

- Environmental Product Declarations (EPDs); and
- Databases.

EPDs are '*verified documents that report environmental data of products based on Life Cycle Assessment'* in accordance with the international standard ISO 14025 (Häfliger et al., 2017). Refer to Figure 2-14, which is the EPD for a concrete block material, for the disclosure of information about environmental impacts and resource use for the product. If there is more than one EPD available for a material, it is common to calculate the average value for use in the assessment (Häfliger et al., 2017).

DESCRIPTION OF THE SYSTEM BOUNDARY (X = INCLUDED IN LCA; MND = MODULE NOT DECLARED)

PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END OF LIFE STAGE				BENEFITS AND LOADS BEYOND THE SYSTEM BOUNDARIES
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	MND

RESULTS OF THE LCA - ENVIRONMENTAL IMPACT: 1m3 Generic Precast Aerated Concrete Block

Parameter	Unit	A1-A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
GWP	[kg CO_2-Eq.]	168.00	3.62	1.10	-57.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.08	1.43	0.97
ODP	[kg CFC11-Eq.]	7.10E-7	2.45E-12	5.80E-12	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	1.41E-12	1.48E-11	1.07E-11
AP	[kg SO_2-Eq.]	2.08E-1	1.51E-2	6.84E-4	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	8.67E-3	9.81E-3	5.78E-3
EP	[kg $(PO_4)^{3}$-Eq.]	1.99E-2	3.70E-3	1.09E-4	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.12E-3	2.37E-3	7.86E-4
POCP	[kg ethene-Eq.]	6.00E-2	-5.66E-3	6.68E-5	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	-3.25E-3	1.43E-3	5.55E-4
ADPE	[kg Sb-Eq.]	2.87E-4	6.80E-8	1.58E-7	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	3.90E-8	2.53E-6	3.32E-7
ADPF	[MJ]	1.20E+3	4.98E+1	1.81E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.86E+1	2.69E+1	1.25E+1
Caption	GWP = Global warming potential; ODP = Depletion potential of the stratospheric ozone layer; AP = Acidification potential of land and water; EP = Eutrophication potential; POCP = Formation potential of tropospheric ozone photochemical oxidants; ADPE = Abiotic depletion potential for non-fossil resources; ADPF = Abiotic depletion potential for fossil resources														

Figure 2-14 Environmental Product Declarations (EPD) for a concrete block (IBU, 2017)

On the other hand, several databases cover the environmental data for construction materials. The following provides details of existing databases for estimations of embodied carbon, based upon the following information from De Wolf et al. (2015):

- Carbon Working Group (CWG);
- Inventory of Carbon & Energy (ICE); and

- Database of embodied Quantity outputs (deQo).

The CWG, which is based in the US, holds data on the amount of embodied carbon that is found in the most commonly employed construction materials (De Wolf et al., 2015). This group has also emphasised the variability in data quality, which leads to uncertainty over its accuracy (Webster et al., 2012), as different assumptions could be made by the varying sources (De Wolf et al., 2014; Eleftheriadis et al., 2018). It can, however, be observed that the quality of the data used in terms of geographical setting, variability, and consistency plays a leading role in influencing uncertainty in the energy and carbon-embodied coefficients (De Wolf et al., 2014).

The ICE is a comprehensive open source database in the United Kingdom introduced by the University of Bath (Hammond and Jones, 2011a). The ICE is also considered the most reliable data on carbon and energy-embodied coefficients (MJ/kg or $kgCO_2e/kg$), but only for the cradle-to-gate stage (Hashemi et al., 2015; Vilches et al., 2017; Kupwade-Patil et al., 2018). To correctly estimate the complete building lifecycle (cradle to grave), some hypotheses need to be made because a building's future lifecycle cannot be predicted in advance with complete certainty (Hammond and Jones, 2011b). Data from the ICE are attached in Appendix E (Table 1).

In the construction industry, deQo is output data; a valuable online interactive tool has been developed that provides information on *'the cradle-to-gate embodied carbon of structures'* (De Wolf et al., 2017a), which allows comparisons to be made on global warming potential (GWP) weighted as $kgCO_2e/m^2$ of the already constructed buildings. The deQo serves as an online database that researchers, engineers, and architects can use to input the details of their projects and compare them to other projects that have already been completed (De Wolf et al., 2017a). For example, plotted ranges can be used by structural engineers to gauge where within this range their own design projects fall. Figure 2-15 illustrates the targeted and typical ranges; the former fall within the 25% of the lowest existing buildings, whereas the latter fall within 75% of all existing buildings (De Wolf, 2017). One of the drawbacks of deQo is that it is not possible to view complete details of each project due to issues such as intellectual property rights (Heeren and Fishman, 2019).

		Targeted range ($kg_{CO_{2e}}/m^2$)	Typical range ($kg_{CO_{2e}}/m^2$)
Program Type	Commercial & Residential	90 – 220	220 – 430
	Infrastructure	130 – 230	230 – 550
	Industrial	540 – 670	670 – 940
	Educational	110 – 250	250 – 520
	Healthcare	120 – 260	260 – 450
	Other	35 – 260	260 – 500
Main Structural Material	Concrete	110 – 270	270 – 440
	Steel	120 – 230	230 – 540
	Timber	50 – 170	170 – 300
	Masonry	150 – 210	210 – 260
	Composite	90 – 250	250 – 520
Number of floors	1 – 10	30 – 230	230 – 440
	11 – 50	110 – 210	210 – 400
	51 – 100	270 – 370	370 – 610
	> 100	230 – 340	340 – 630
Size (m^2)	<10,000	30 – 230	230 – 490
	10,000 – 100,000	100 – 250	250 – 440
	> 100,000	220 – 280	280 – 500

Figure 2-15 Target and typical ranges of embodied quantity outputs (De Wolf, 2017).

The widespread practice of sustainability has not been fully adopted to date in Saudi Arabia, so integrating LCAs into working practice could be very effective in this regard; however, LCAs are still uncharted territory for much of the Saudi construction industry (Asif et al., 2017). To make LCAs successful, collaboration between all involved stakeholders is needed, as different parties may need to compromise in terms of quality, financial investment, company image, and the types of raw materials used (Zutshi and Creed, 2015). In Saudi Arabia, Youssef and Hamid (2014) identified a significant concern about not having access to a common library of data containing information about materials such as thermal properties for building energy simulation, which is associated with shortage of skills and tools; this was after conducting a survey that targeted design offices (14), construction contractors (13), and materials suppliers (14). Furthermore, Asif et al. (2017) stressed that when using LCA in house building, there is a lack of public datasets for products and materials (embodied impacts) in the country—see Section 2.3.1, which discussed the environmental impacts of construction materials for a domestic building in Saudi Arabia which used LCA. Therefore, there is a need to search elsewhere for data that can be used to create the framework (RESAF). This research uses the database ICE version 2: Inventory of Carbon & Energy—see Section 4.2.1 for the justification of using this database (ICE).

2.5.1.2. The Green Guide to Specification: an environmental profiling system for building materials and components

The Green Guide to Specification is a benchmarking database that uses LCA. It was established through cooperation between the Building Research Establishment (BRE) in the UK and Anderson et al. (2009). It enables users to categorise the materials and components that go into the construction of a building in terms of how environmentally friendly they are. The categories run from A+ to E. It also provides specific measures (i.e., kg and %) to refer to such characteristics as the content that can be recycled, embodied carbon, climate change, and water extraction (Anderson et al., 2009). These are illustrated in Figure 2-16. There are many similarities with the LCA approach, but this approach extends to the use of Ecopoints; these are weightings that are assigned by stakeholders (Hunt et al., 2014).

Solid concrete ground floors Domestic	Element number	Summary Rating	Climate change	Water extraction	Mineral resource extraction	Stratospheric ozone depletion	Human toxicity	Ecotoxicity to freshwater	Nuclear waste (higher level)	Ecotoxicity to land	Waste disposal	Fossil fuel depletion	Eutrophication	Photochemical ozone creation	Acidification	Typical replacement interval	Embodied CO_2 (kg CO_2 eq.)	Recycled content (kg)	Recycled content (%)	Recycled currently at EOL (%)
Plywood (temperate, EN 636-2) decking on vapour control layer, on timber battens and insulation on (cont'd):																				
in situ concrete floor on polyethylene DPM on blinded recycled aggregate sub-base	820100028	D	A	E	B	D	E	E	D	C	E	D	D	D	C	40	65	332	38	89
in situ concrete floor on polyethylene DPM on blinded virgin aggregate sub-base	820100027	E	A	E	D	D	E	E	E	C	E	D	D	D	C	40	65	2.3	0	88

Figure 2-16 Example of how a Building Research Establishment categorises materials and components at the system level (Anderson et al., 2009)

A further benefit of the guide is that it automatically varies the materials employed in the calculations to match the purpose of the building; therefore, it takes into account the relationships between different building types and the materials used to construct them (Ilhan and Yaman, 2016). For example, the building elements incorporated into the calculations for a commercial building will differ from those included for housing—and not only the elements, but their quantities and environmental impact will also vary.

However, the guide has been criticised by Khasreen et al. (2009) because it assigns projects an overall grade but does not contain enough information for manufacturers to improve their production processes. The fact that the database is built on a limited range of materials could also constrain innovative design thinking, as it makes it challenging to confidently apply generic information to a specific case (Khasreen et al., 2009). Therefore, any newly developed method of assessment will need to provide information on how the database and its outputs are generated so that the testers can change the building elements in a positive way; this will be considered when generating the RESAF framework later in this research.

2.5.1.3. Leadership in Energy and Environment Design (LEED)

LEED assessment has been developed by the United States Green Building Council (USGBC). It uses a points system to evaluate a building's sustainability. It covers a number of categories (criteria assessment), and each category is allocated a certain number of points (see Table 2-13 – Section 2.5.3.) (USGBC, 2020). Based on the total achieved points, a project will be awarded from certified to platinum grade; see Figure 2-17.

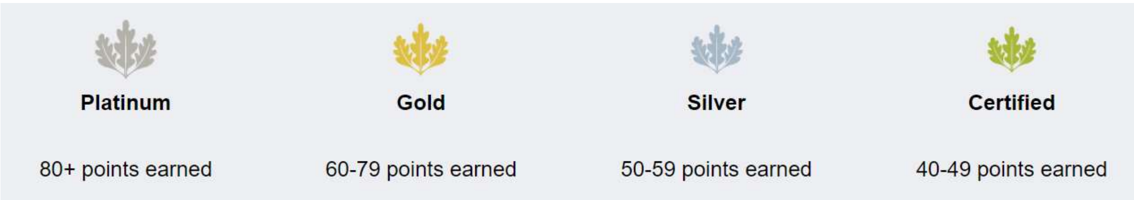


Figure 2-17 LEED certified grades (USGBC, 2020)

The following are notable points in the LEED assessment:

- Currently, according to Alyami et al. (2015), the only assessment system used in Saudi Arabia is LEED, not because it is the best method for assessing sustainability levels, but because it is founded on preferences based on politics and trade. Although the LEED rating assessment has been developed and diversified over the years, which has enabled it to handle sustainability issues, LEED and the principles of resilient design have revealed gaps as well as querying the suitability of Saudi Arabian context (Section 2.5);

- It gives more attention to the energy (building operation stage) (Meneghelli, 2018); because of this, it gives a higher point to energy, which is around 36% compared to around 10% for materials;
- There is a challenge, or it could be called a concern, that when an energy performance has been assessed during the design stage, it will differ in the operation stage due to, for example, changes made during the construction process (Amiri et., 2019); and
- LEED involves complex processes to perform the assessment when it comes to some countries like Saudi Arabia, for example, stakeholders' interests, engineers' or designers' lack experience, time, and cost (Ismaeel, 2019).

2.5.1.4. Building Research Establishment Environment Assessment Method (BREEAM)

BREEAM is an offshoot of the BRE in the UK (BREEAM, 2016). It uses a weighting system to determine a building's sustainability; see Table 2-12. For the categories of the criteria of assessment and allocated weighting (%), refer to Table 2-13 – Section 2.5.3.

Table 2-12 BREEAM project rating

BREEAM Rating	Score (%)
OUTSTANDING	≥ 85
EXCELLENT	≥ 70
VERY GOOD	≥ 55
GOOD	≥ 45
PASS	≥ 30
UNCLASSIFIED	< 30

In summary, a BREEAM assessment's notable points are that it gives a 10% bonus under innovation category (BREEAM, 2016), so buildings have the opportunity to gain additional points during the assessment process. In addition, BREEAM gives a 12.50% material category. Indeed, based on Banani et al. (2016), BREEAM is stringent compared to other assessments in terms of using local materials.

2.5.1.5. The Building Resilience Rating Tool (BRRT)

The Insurance Council of Australia (ICA) developed the Building Resilience Rating Tool (BRRT). Its purpose is to evaluate the resilience of houses in order to provide information to insurers about how buildings will fare when they face different hazards (ICA, 2019) such as cyclones, earthquakes, floods, bushfires, and severe hail or rain (see Figure 2-18). The data about these hazards are combined with data on the characteristics of the materials and the design of a building, and together, they provide a measure of resilience (Burroughs, 2017). In other words, the characteristics of a building influence how it responds to these hazards, and these, therefore, include the materials of the external walls and their strength, the height of each floor, the type of cladding used on the roof, and the type of external doors and windows used (Burroughs, 2017). However, this tool is not suitable for use in this study because it encompasses only resilience risks; for this research, it was considered more suitable to utilise a tool that delivers a wider concept of resilience, including such elements as social or policy effects.

Figure 2-18 How the tools work (ICA, 2019)

2.5.1.6. Designing a Resilient Cities Guide

Lombardi et al. (2012) developed this guide for urban futures' assessment, which is used to determine the resilience (future-ability in 40 years—average time of a regeneration cycle) of sustainability solutions according to scenario-based research, covering United Kingdom urban sites (Hunt et al. 2012). The scenarios are categorised into four domains:

A. The sustainability paradigm (people drive change);
B. Policy reform (policy drives change);

C. Market forces (the market drives change); and

D. Fortress world (instability and chaos drive change).

It takes into account the number of necessary conditions (also known as issues) including air quality, energy consumption rates, biodiversity, water usage, ground infrastructure, the environment surrounding the building, the level of innovativeness required, the decisions to be made, organisational behaviour, policies, social needs, and aspirations (Lombardi et al., 2012). These conditions will be assessed in terms of indications of the likelihood that a condition will continue into the future. The grade levels are as follows:

A. Light green means likely to continue;

B. Amber means at risk; and

C. Red means very unlikely to continue.

See Section 4.3 for detailed explanations of how this design guide works.

An example of an assessment can be seen in Figure 2-19. In the example, the proposed solution is (local sourcing of construction materials to reduce carbon footprint), and one of the necessary conditions is (consumers support local sourcing). It gained an amber grade when it was assessed against the policy reform scenario; this is due to the behaviour of the consumers (basically, they ignore the policy); see red circles in Figure 2-19.

This guide will be utilised in this research when RESAF is developed for the following reasons:

A. Once the solutions have been proposed (in the case of RESAF, the selected materials), using this guide will ascertain how likely it is that these proposed solutions will cope with possible future conditions, as the guide is an effective and structured way of thinking about the proposed solutions;

B. If the guide succeeds in creating a framework to evaluate buildings' sustainability performance, further research will be required to answer the additional questions that will undoubtedly emerge and to improve the framework (Marjaba and Chidiac, 2016). In the case of RESAF, implementing this guide within the framework will ensure the future ability of the selected materials; and

C. Levels of sustainability must continue to improve and must not remain static; therefore, it is essential to make regular evaluations and maintain improvement (Bakhoum and Brown, 2012); this guide will ensure this point is considered within RESAF.

Local sourcing of construction materials to reduce carbon footprint

Necessary conditions	New Sustainability Paradigm	Policy Reform	Market Forces	Fortress World
Incentives (financial and non-financial) to encourage local sourcing	Local sourcing is encouraged and supported by social and environmental policy and values. Support mechanisms are in place to encourage local sourcing	Increasing environmental concerns drive policy towards more local sourcing of products and materials used in construction	Profit making is at the core of business activities. Local supplier decision is driven by cost. Desirable if local products' high quality enable high value for the developers	For the poor, environmental concerns are secondary. The rich may choose to source locally if it is perceived to address their resource and security concerns
Consumers support local sourcing	The local population recognises environmental responsibilities and supports local products	Some consumers ignore policy guidelines. Behavioural change is slow and uptake of locally sourced products may take time	Consumers prefer global brands with international reputation. However, local materials inevitably become cheaper because of increasing transport prices	The poor have no choice but to opt for whichever products are available. The rich may choose to source locally if it is perceived to address their resource and security concerns
Materials are available locally	Environmental priority means reclaimed materials in particular are managed judiciously	Policy drives market for local materials, but global markets compete with local markets	Materials flow to regions with specialised infrastructure. National construction companies may not operate at regional/ local level – instead all sourcing is done nationally	Rich control resources, so materials are available. Poor are accustomed to working with local materials

Figure 2-19 Example of assessing the resilience of possible sustainable solutions in the future (Lombardi et al., 2012)

2.5.2. Available sustainable codes and guides in Saudi Arabia

The following section provides an overview of the innovations initiated by Saudi Arabian organisations and the building assessments developed specifically for Saudi Arabia.

2.5.2.1. The Saudi Energy Efficiency Centre (SEEC)

The energy efficiency programme introduced by the Saudi Energy Efficiency Centre (SEEC) in 2010 aimed to raise awareness among Saudi citizens of the need to improve the country's energy efficiency. The aim was to help preserve Saudi Arabia's national energy resources (SEEC, 2019) through education, regulation, audits, and load management (Krarti et al., 2017). Al-Saud (2014) highlighted how this programme resulted in positive changes in the building sector. Initially, the programme focused on raising minimum energy performance standards (MEPS). It did so by making it compulsory for thermal insulation to be included in all new buildings and by creating efficiency labels for key home products. Products issued with these new labels included home appliances, such as tumble driers and washing machines, air conditioners, and cars. The Saudi Standards, Metrology, and Quality Organization (SASO), established in 1972, issues the labels, and this allows consumers to easily compare products in terms of their energy efficiency—hopefully helping them to choose the more energy-efficient technologies. The higher the energy efficiency indicated on the label, the less energy the product consumes. The label also includes basic data about the product (product type, model, and brand, energy consumption, and test standard) (SASO, 2019). The label grades the product from A to G based on the energy efficiency; for example, the air conditioner shown in Figure 2-20 scored C. The efforts also being made to issue codes indicating a building's energy efficiency and sustainability are discussed in Section 2.5.2.2.

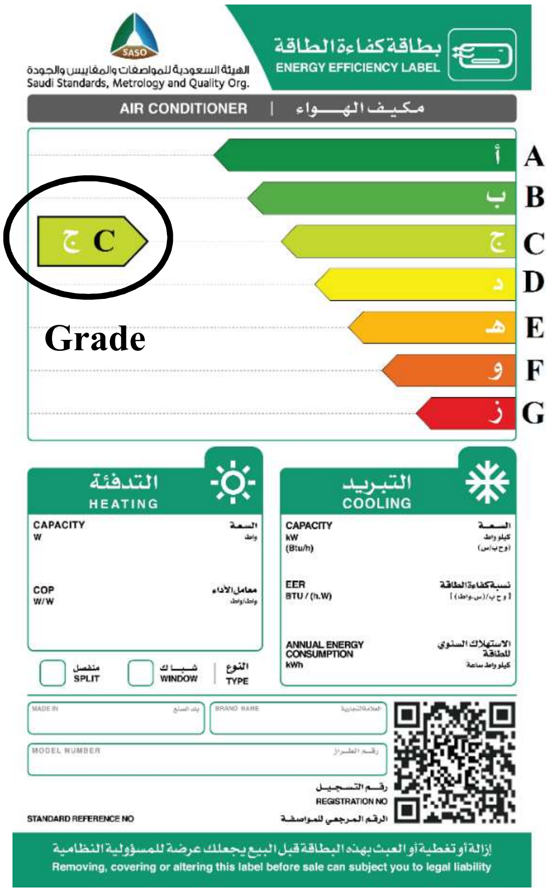
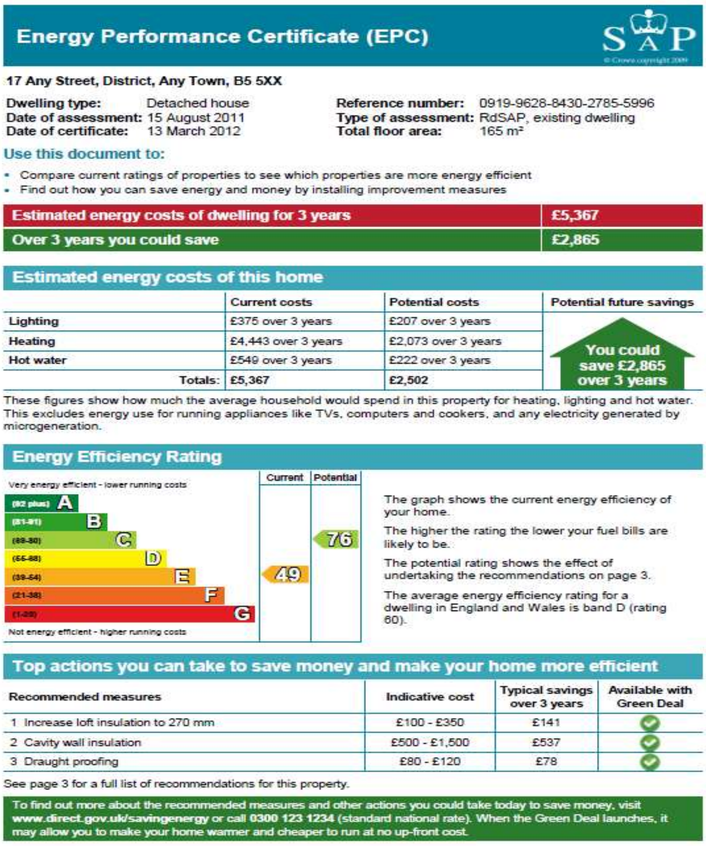


Figure 2-20 A sample of energy efficiency label (SEEC, 2019)

Energy Performance Certificates (EPCs) are a compulsory requirement for domestic buildings in the UK. The certificate's primary role is to provide information to potential buyers and tenants about a building's energy performance, as well as suggesting ways in which the energy performance can be improved. The energy efficiency rating allocated to a building is correlated with its running costs, and these are based on the materials used in the building and its services—for example, how it is heated, the level of insulation, and the recommendations to reduce the in-use energy; see Figure 2-21 (Department for Communities and Local Government, 2017). A similar system might be useful for implementation in Saudi Arabia for new and existing housing, especially if it takes into consideration the consumed energy and carbon footprint of the materials utilised in both the construction and operation of the building. In September 2019, the SASO introduced a new quality control for cement products (see Figure 2-22) (SASO, 2019). However, there is still a need to enforce environmental declarations for building materials rather than just enforcing quality control for manufacturing. This may focus attention on the measures of these materials' footprint.



Energy Performance Certificate (EPC)

SAP

17 Any Street, District, Any Town, B5 5XX

Dwelling type: Detached house
Date of assessment: 15 August 2011
Date of certificate: 13 March 2012
Reference number: 0919-9628-8430-2785-5996
Type of assessment: RdSAP, existing dwelling
Total floor area: 165 m²

Use this document to:

- Compare current ratings of properties to see which properties are more energy efficient
- Find out how you can save energy and money by installing improvement measures

Estimated energy costs of dwelling for 3 years	£5,367
Over 3 years you could save	£2,865

Estimated energy costs of this home

	Current costs	Potential costs	Potential future savings
Lighting	£375 over 3 years	£207 over 3 years	You could save £2,865 over 3 years
Heating	£4,443 over 3 years	£2,073 over 3 years	
Hot water	£549 over 3 years	£222 over 3 years	
Totals:	£5,367	£2,502	

These figures show how much the average household would spend in this property for heating, lighting and hot water. This excludes energy use for running appliances like TVs, computers and cookers, and any electricity generated by microgeneration.

Energy Efficiency Rating

The graph shows the current energy efficiency of your home.

The higher the rating the lower your fuel bills are likely to be.

The potential rating shows the effect of undertaking the recommendations on page 3.

The average energy efficiency rating for a dwelling in England and Wales is band D (rating 60).

Top actions you can take to save money and make your home more efficient

Recommended measures	Indicative cost	Typical savings over 3 years	Available with Green Deal
1 Increase loft insulation to 270 mm	£100 - £350	£141	✓
2 Cavity wall insulation	£500 - £1,500	£537	✓
3 Draught proofing	£80 - £120	£78	✓

See page 3 for a full list of recommendations for this property.

To find out more about the recommended measures and other actions you could take today to save money, visit **www.direct.gov.uk/savingenergy** or call **0300 123 1234** (standard national rate). When the Green Deal launches, it may allow you to make your home warmer and cheaper to run at no up-front cost.

Figure 2-21 A sample of an Energy Performance Certificate (Government of United Kingdom, 2012)

Figure 2-22 Quality control mark for concrete (SASO, 2019)

2.5.2.2. The Saudi Building Code National Committee

The Saudi Building Code (SBC) National Committee has failed to make itself well known among the construction industry within Saudi Arabia, which means that it has not been effectively utilised (Al Surf et al., 2013a;2013b). It has collaborated with the SEEC to determine how building energy-efficiency mechanisms can be enhanced. Regarding the public buildings already built, these will be retrofitted to improve their energy use, and a financial scheme will be introduced to provide an incentive for owners of residential buildings to replace energy-inefficient products with new, more efficient ones (Al-Saud, 2014). This is in line with the strategies adopted in many European countries, not least the UK, where the green deal is a relevant example of finance initiatives.

A number of amendments were made to the building codes in November 2018 by the SBC, including the Saudi Energy Conservation Code—Low-Rise (residential) Buildings (SBC 602)—as well as the recently introduced Green Building Code (SBC 1001) in 2020, which states that buildings used for housing must implement the codes by 20 August 2020 (SBC, 2018a; 2018b; 2020). All the measures taken by the SBC aim to optimise the energy efficiency of new buildings (Felimban et al., 2019). With the SBC 602 and 1001 code, a copy of the requirements has been released, but there is no sign of the requirements and commentaries copy, and the same applies for many of the other codes (SBC, 2018a; 2018b; 2020) (see Figure 2-23). This research consulted SBC 602 and 1001 (see Chapter 5) for the case study in order to make sure that it complied with the relevant regulations. The main issue with the new codes is that people working in the industry do not yet know about them, or if they do, they do not yet have a copy of them. Ahmed et al. (2019) highlighted this issue of a majority of professionals being unaware of the Saudi Energy Conservation Code as shown in a survey (47 out of 57 professionals reached). This problem will be discussed in more detail in Appendix D, which includes interviews with experts in Saudi Arabia that raise this issue again.

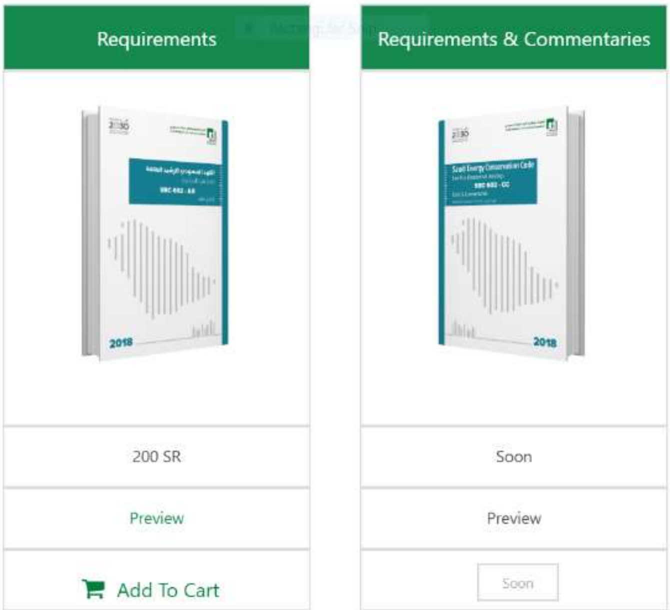


Figure 2-23 Copies for the Saudi Building Code (SBC) 602

2.5.2.3. The Saudi Green Building Forum

The Saudi Green Building Forum (SGBF) is a nongovernment organisation that has consultative status with the United Nations. It has government support, and its mandate is to raise awareness of sustainability in Saudi Arabia. Its four principal goals are as follows (SGBF, 2017):

1) Promoting green buildings;
2) Identifying how policies can encourage urban development while preserving Saudi Arabia's cultural heritage;
3) Integrating innovative technological tools into construction; and

4) Introducing regulations that support green buildings and green building rating systems, for example, LEED.

Aboneama (2018) raised the following question regarding SGBF: Will any changes be made to the LEED item weights to take into account Saudi Arabia's unique environment? Unfortunately, this is not currently the case; even though the environments of the United States and Saudi Arabia are vastly different, the LEED certificates issued in Saudi Arabia carry the same items and weights as those in the United States.

2.5.2.4. The Saudi environmental assessment method (SEAM)

A tool for assessment introduced by Alyami et al. (2015), the SEAM is illustrated in (Table 2-13 – Section 2.5.3), and the rating benchmark is in Figure 2-24. As water is a scarce resource in Saudi Arabia, water efficiency is weighted heavily in this tool. In contrast, there is an abundance of sunshine and thus of solar energy, which is environmentally friendly, sustainable, and reliable. After water, solar energy was weighed as the second priority as per the SEAM tool—a suitable strategy to diversify energy supplies whilst significantly reducing carbon emissions.

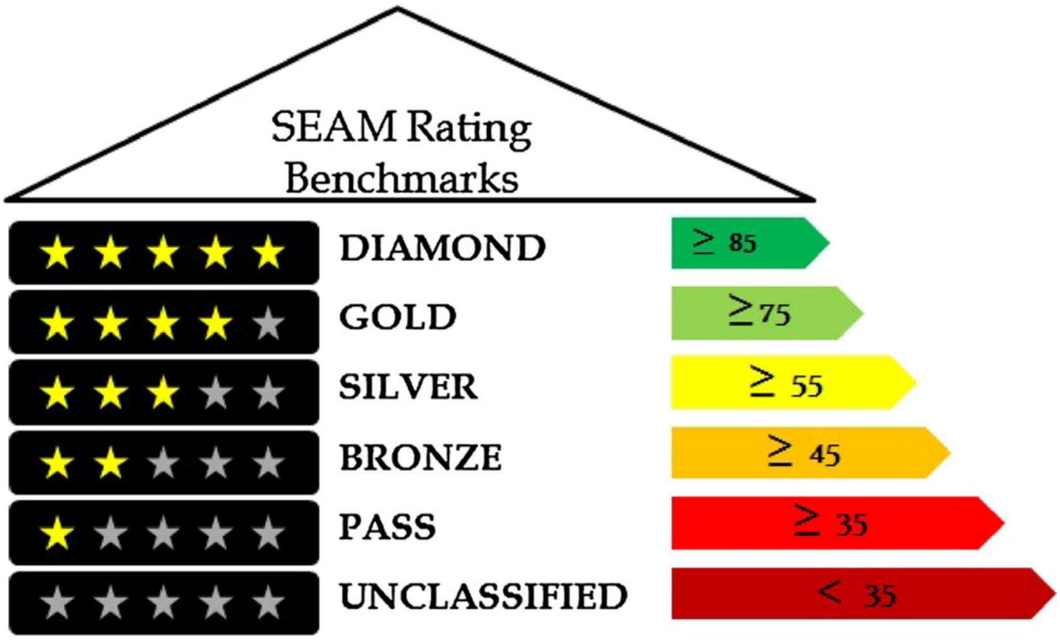


Figure 2-24 SEAM rating for projects (Alyami et al., 2015)

Alyami (2019) recommended that, initially, the SEAM tool should not be employed based on prerequisite criteria. However, there is a new proposition (building professionals should agree on the prerequisite criteria) that has yet to be implemented. Once it has been verified, building companies will be able to use the SEAM on the prerequisite criteria. Saudi Arabia experiences different environmental conditions compared to other countries. However, despite these unique conditions, the SEAM assessment gives a lower weighting to energy (18.4%) than does LEED (36.50%), and it is very similar to BREEAM (19%). This is contradictory to the high demand for energy in Saudi Arabia (see Section 2.3.2); therefore, energy should be given a higher weighting in the assessment, as the energy demand must somehow be reduced. In the SEAM assessment, materials account for only 6.4% compared with the much higher ratio of 30% in BREEAM and 10% in LEED. The fact that materials do not have a significantly higher rating in Saudi Arabia is a point of concern.

2.5.2.5. Low carbon domestic design framework

The use of low-energy building methods in Saudi Arabia can be achieved by applying a *'low carbon domestic design framework'* in Figure 2-25, as proposed by Aldossary et al. (2015a) and Aldossary (2015). The framework approach takes into account the incorporation of four dimensions (design of architectural principles, building fabric, on-site renewable energy, and cultural aspect) and offers design concepts related to these dimensions. For example, in the building fabric dimension, it provides design concepts such as using low conductivity materials, efficient types of insulation, and hermetically sealed windows, which in return, will help with low energy and carbon during the operation of the building (please refer to Figure 2-25 for the full details of the framework dimensions and the design concepts). However, the framework strategy does not consider the environmental embodied impacts of materials and does not provide an assessment of the resilience of the proposed solutions. In reality, Aldossary (2015) recommended researchers to look into embodied energy and carbon for construction materials in future research.

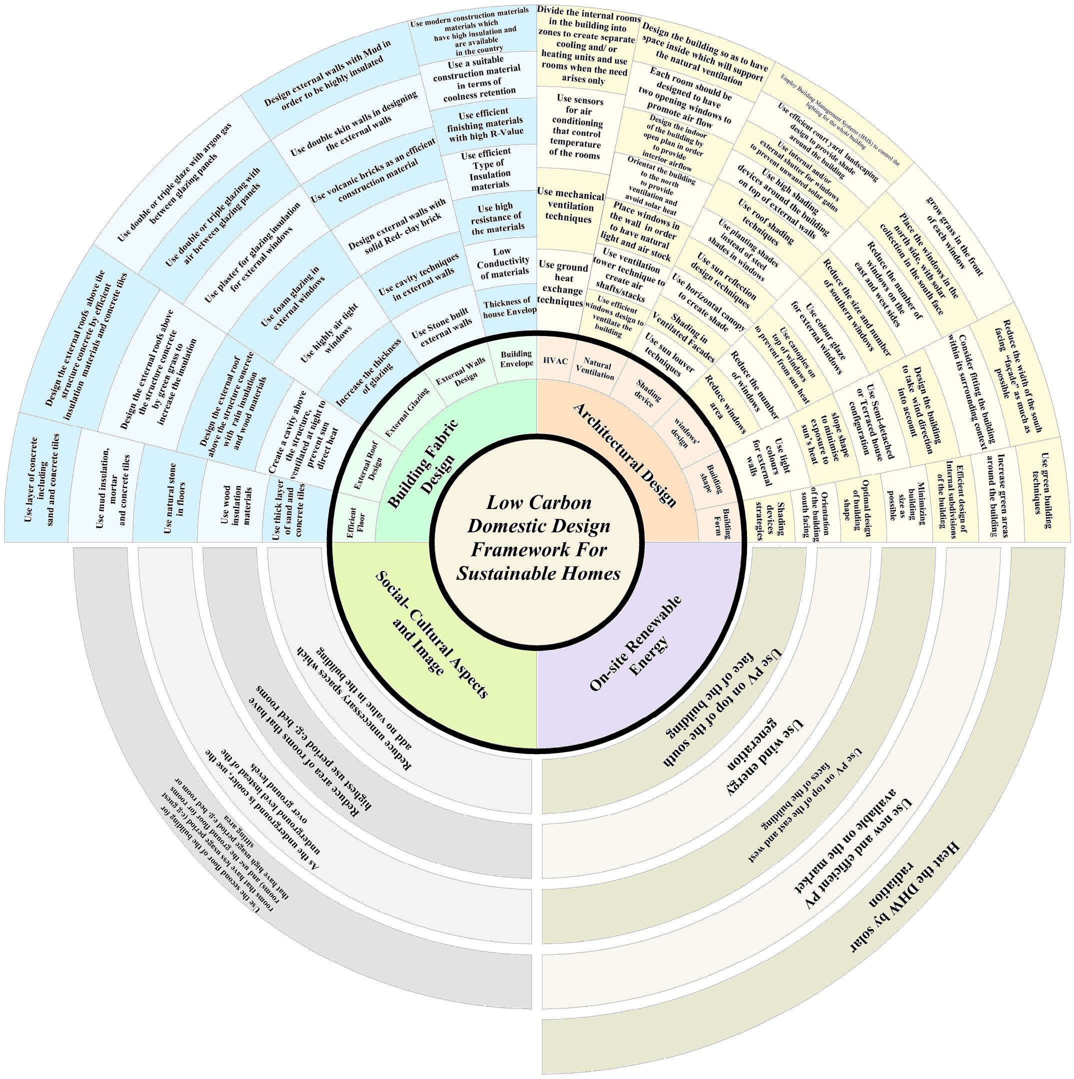


Figure 2-25 A framework for low carbon design (Aldossary et al., 2015a; Aldossary, 2015)

2.5.2.6. Model for Sustainability development in housing

A model developed by Al Surf (2014; 2017) focused on the development of sustainable housing in Saudi Arabia, as presented in Figure 2-26. This model is divided into two layers: barriers to sustainability as well as critical success factors (CSFs); both are related to four main aspects (social, environmental, economic, and applications). In short, this model presents the barriers to implementing sustainability housing in the country and suggests solutions for these barriers. For example, in the application aspect, one of the barriers is (lack of sustainability awareness from design offices) in the country; then, the presented CSFs are (i.e., enforce new regulations and educate the design offices about sustainability); full details are given in Figure 2-26. Notably, this model covers a wide range of subjects for sustainability solutions (from rules and regulations to the use of green energy). However, in the context of construction materials, the energy and carbon embodied impacts as well as the resilience of the proposed solutions were not part of the scope of the model.

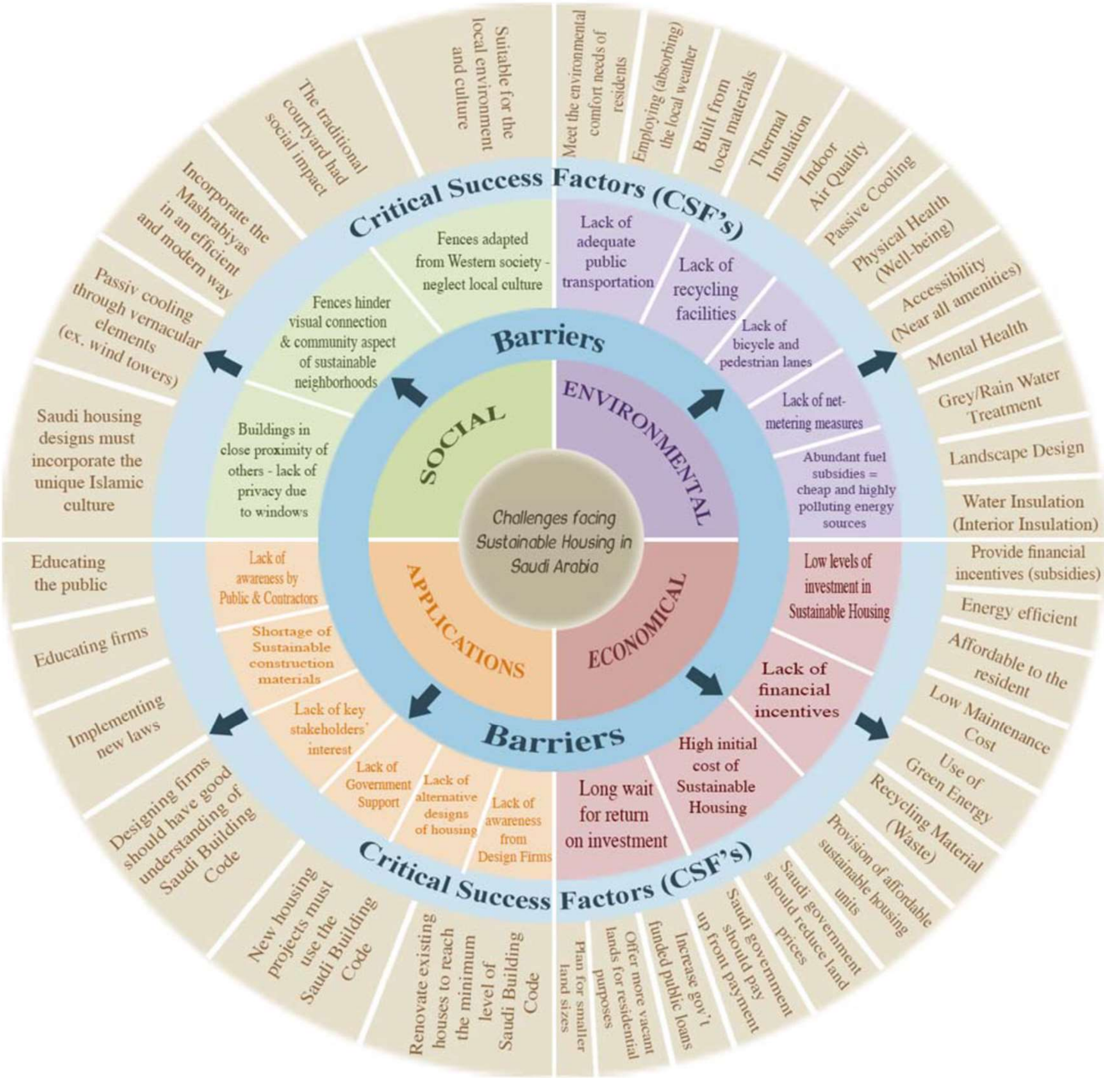


Figure 2-26 Model for housing targeting sustainability development (Al Surf, 2014; 2017)

2.5.2.7. Mostadam

The Saudi Ministry of Housing introduced the Mostadam assessment tool, which is a weighting system that assesses buildings out of a total of 100 points (Mostadam, 2019).

The weight given to energy is 27 points (27%), which appears to be reasonable in comparison with the other tools, as it lies in between LEED (36.50%) and BREEAM (19%). However, materials and waste account for only 4%. This percentage is clearly insufficient when compared with LEED and BREEAM; for example, BREEAM gives 13% for materials and waste. Furthermore, it seems that cement products are not taken into account by the Mostadam assessment, which is a clear oversight, as concrete has been shown to have a high environmental impact (Asif et al., 2017). Using low-carbon concrete should, therefore, be assigned points.

During the interviews for this research in Saudi Arabia, one of the sustainability experts commented that only 10% of the Mostadam assessment is about sustainability; therefore, the expert found it unsatisfactory (see Appendix D). Other sustainability experts agree that the main concern of the Mostadam assessment seems to be how the construction is supervised rather than environmental or sustainability aspects, even though the tool aims to promote sustainability. It is, perhaps, too early to be commenting on the correct implementation of the assessment, as it is still in its initial phases.

2.5.3. International and local tools or guides remarks

Table 2-13 presents the values of categories (site, energy, water, indoor environment quality, material, waste, pollution, management, and other) for different assessments. Examination of each assessment reveals clear differences in the allocated percentage of each category. This is because each assessment is developed based on criteria that might reflect the context and conditions of the country of origin (Banani et al., 2016; Vyas et al., 2019).

In addition, all the green building rating tools (LEED, BREEAM, SEAM, and Mostadam) emphasise energy credits. Indeed, the energy category is always higher than the other categories, although there is a difference in how great a percentage of energy has been allocated; for example, the LEED assessment allocates a higher percentage (36%). This higher allocation is based on energy issues in relation to fossil fuel and environmental impacts. The current predictions of energy demand will continue to increase in the future, so assessments need to give energy a high percentage to encourage savings in demand (Kamaruzzaman et al., 2016; Illankoon et al., 2017a; 2017b).

Surprisingly, most of the assessments (LEED, SEAM and Mostadam) have allocated lower percentages to materials; however, BREEAM allocates around 12%, which is higher than other assessments. Baharetha et al. (2012) stated that there is inconsistency between the sustainability assessments about the construction materials. These low percentages are in line with the role of materials in the building industry; Olawumi et al. (2020) stated that one third of consumed materials globally is due to the construction process.

Table 2-13 Available assessments criteria

Tools	**LEED v4.1 (residential)** (USGBC, 2020).		**BREEAM International** (BREEAM, 2016)	**SEAM** (Alyami et al., 2015)	**Mostadam** (Mostadam, 2019)	
	Points	%	%	%	Points	%
Site	15	13.64	18	5.40	16	16
Energy	40	36.36	19	18.40	27	27
Water	15	13.63	6	25.80	24	24
Indoor Environment Quality	16	14.55	14	12.70	14	14
Material	12	10.91	12.50	6.40	4	4
Waste			7.50	6.80		
Pollution	Considered within other aspects		10	8.30	Considered within other aspects	
Management	2	1.82	12	4.90	4	4
Other	10	9.09	1	11.30	11	1
Total	110	100	100	100	100	100

Regarding the frameworks (see Section 2.5.2.5 – Figure 2-25 and Section 2.5.2.6 – Figure 2-26), there are two frameworks available in the literature review that consider housing in Saudi Arabia; one was developed by Aldossary et al. (2015a) and Aldossary, (2015), and the other was developed by Al Surf (2014; 2017) for sustainable housing. Both offer a wide range of solutions (concepts) for sustainability purposes; the first one focuses on low carbon design strategies for the house itself, and the second one focuses on sustainability strategies in general for the house itself and other points (i.e., codes, regulations, and recycling materials facilities).

2.6. Literature review of the methodological process

A systematic search was conducted to select the references to target sustainability and resilience in the context of Saudi Arabian domestic buildings. Therefore, for the better application of this method, reviews that used this method in a similar topic area (sustainability and resilience) were read specifically for the list of references captured from the literature; see examples Wolf et al., 2014, Browning and Rigolon, 2019, Mensah and Ricart (2019) and Topal et al. (2020). In relation to this study, there are three groups of papers:

A. Papers that target sustainability;
B. Papers that target resilience; and
C. Papers that target sustainability and resilience.

To capture the related reference, an Internet search using Scopus and Web of Science websites was conducted to identify peer-reviewed references. The search for Title/Abstract/Keywords of the published references was done by using keywords related to the groups (A), (B), and (D); see Figure 2-27. An important note to make sure the search captures all related papers (energy and environmental were main keywords, to ensure all related topics, as some papers may not mention sustainability in the Title/Abstract/Keywords). The inclusion and exclusion criteria are as follows:

- For group (A), the inclusion criteria include references that focus on sustainability in the subjects of domestic buildings (with linked words such as domestic, residential and others) concentrating on the subjects of energy or construction materials. The exclusion criteria are as follows: Saudi Arabia not considered, or study topics not related to the study focus, such as water, food, power systems, mechanical engineering and economics. The search identified 268 references; however, after reading the titles and abstracts, the number of references decreased to 78. Next, following reading through the full texts, the number decreased to 41. These references can be divided as follows:

A. Construction materials: A house LCA study (Asif et al., 2017) (see Section 2.3.1), waste and recycle materials for construction (Ouda et al., 2018; Blaisi, 2019) (see Section 2.3.1), and availability of data about materials (Youssef and Hamid, 2014) (see Section 2.5.1.1);
B. Frameworks for assessing sustainable housing (Aldossary et al., 2015a; Aldossary, 2015; Al Surf, 2014; 2017) (see Sections 2.5.2.5 and 2.5.2.6) and the shortcomings in available sustainable assessments in respect to Saudi Arabian context and conditions (Attia, 2013; Al Surf, 2017) (see Section 2.5);
C. Energy: **Current energy consumption** (see Section 2.3.2.1) (Alrashed and Asif 2014b; Aldossary et al., 2017; Al Kanani et al., 2017; Krarti et al., 2020), **Reasons for high energy demand** (see Section 2.3.2.2) (Choguill, 2008; Taleb and Sharples, 2011; Alaidroos and Krarti 2015b; Aldossary et al., 2015a; Mujeebu and Alshamrani, 2016; Al Surf, 2017; Abd-ur-Rehman et al. 2018; Ahmed et al., 2019; Alshahrani and Boait, 2019; Esmaeil et al., 2019; Felimban et al., 2019; Almasri et al., 2020; Al-Saggaf et al., 2020; Krarti, 2020; Krarti and Howarth, 2020), and **Solutions of high energy demand** (see Section 2.3.2.3) such as building design (Aldossary et al., 2014a; 2014b; Matar, 2016; Al Kanani et al., 2017; Ghabra et al., 2017; Alghamdi, 2019; Alaboud and Gadi, 2020; Howarth et al., 2020), green roof (Khan and Asif, 2017; Mahmoud et al., 2017; Khabaz, 2018), solar energy (Mujeebu and Alshamrani, 2015; Abd-ur-Rehman and Shakir, 2016; Abd-ur-Rehman et al., 2018), energy retrofits for buildings (Krarti et al. 2020; Krarti and Howarth, 2020), and electrical energy tariffs (Alaidroos and Krarti, 2015b; Matar, 2018).

- For group (B), not all identified available references (170) are related to buildings, as some are related to topics like disaster, water, medical, management, economics, politics, and other included terms of resilience without being considered the study's main focus. As a result, inclusion was based on selecting papers that may indirectly be related to the topic area to give examples of available studies; therefore, after reading the titles and abstracts, the number of papers decreases to 27; then, after reading the full texts, as an example, five papers were selected. Four papers considered "community resilience to disaster" (e.g., Alshehri et al., 2013a; 2013b; 2015a; 2015b) and one paper considered the role of geographic information to identify future hazards (emergencies) (Abdalla and Alharbi, 2017) (see Section 2.4).

- For group (C), (10) papers were found in the search. Inclusion criteria were papers that consider both sustainability and resilience in Saudi Arabia. Exclusion criteria were including only one of sustainability or resilience terms in the abstract or the full text without considering it as the main study focus. The full text of all 10 papers was read; as a result, just three papers were found that studied both terms: Alshuwaikhat and Mohammed (2017), Ndubisi and Al-Shuridah (2019), and Niyazi et al. (2019) All three papers were included because of the limited numbers of papers without any restriction to the topic area (see Section 2.5).

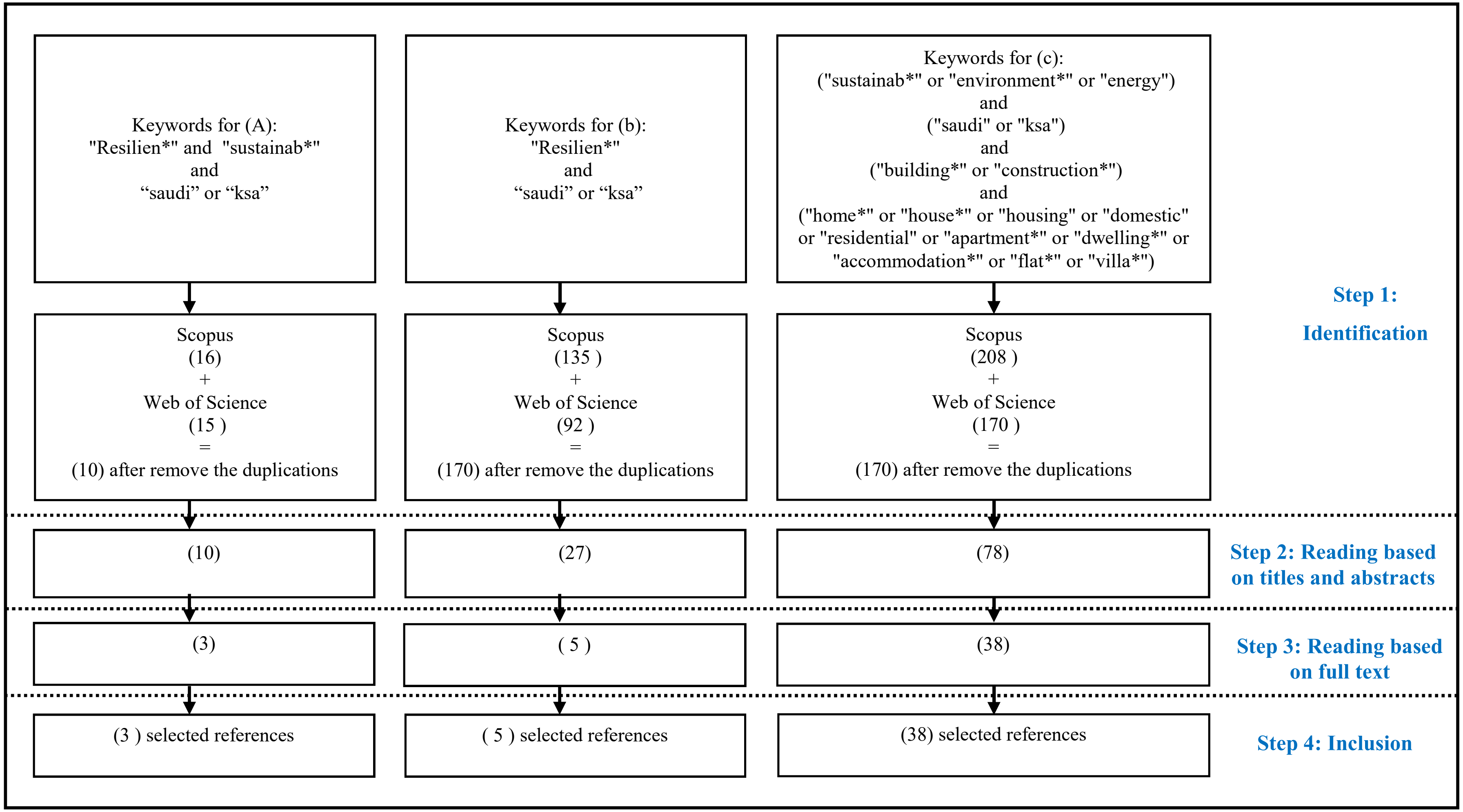


Figure 2-27 References list selection process

2.7. Summary

This review demonstrates that the Saudi Arabian domestic housebuilding sector is in need of a framework that encompasses an assessment of the environmental sustainability and resilience of proposed solutions in Saudi Arabia. Due to Saudi Arabia's unique combination, it is not sufficient to simply employ assessments that have been developed for use in other countries; Saudi Arabia urgently requires its own assessment tool to help decision-making with respect to material selection. While many Saudi organisations are making an effort to improve sustainability, it takes time for these to become effective. To the best of the author's knowledge, to date, there have been no studies in Saudi Arabia that have examined the environmental sustainability of building material selection along with longer term considerations for how buildings operate in terms of energy consumption and carbon emissions. As shown above, housing is a leading consumer of energy, and therefore, improving its energy efficiency will have a huge environmental impact. Carbon footprinting and energy consumption are two quantitative measures of environmental impact and thus deserve attention. This research utilises the LCA assessment principles and the Designing Resilient Cities Guide as a basis for developing a framework for use in the Saudi Arabian housing sector. This framework is discussed further in the following chapters.

3. Methodology

The review of the literature revealed that there are currently no frameworks in existence that allow the resilience and sustainability of the materials used in domestic buildings in Saudi Arabia to be assessed. The methodology described in this chapter therefore aims to generate a framework that will fill this gap in knowledge.

This chapter contains two main parts:

3.1. A general overview of the method steps used in the research project.

3.2. Research methods in general terms that have been used to conduct this research.

Chapter 4 presents, in specific terms, how these methods have been applied in this research.

3.1. General overview of methodology steps used in the research project

These are the methodology steps for the research, Figure 3-1 outlines the methodology briefly in a chart.

M1. Conducting a literature review of sustainability and resilience in general, then in Saudi Arabia (both as independent and combined entities). The review concluded that there is a gap in the literature regarding integrating sustainability and resilience into a single framework for construction materials utilised in domestic buildings in the country. This has already been presented and outlined in Chapter 2.

M2. Designing RESAF using two tools. The first tool is simplified LCA to calculate the embodied energy and carbon for construction materials and the operation of the building, and the second tool is *"urban futures assessment"* to evaluate the resilience of the proposed solutions (in this case, the selected construction materials).

M3. Applying a domestic building at the design stage (using a real case study in Saudi Arabia) to the RESAF beta version, in order to test the framework itself and obtain outcomes (results).

M4a. Validating the RESAF by conducting interviews with experts in the construction and building field in Saudi Arabia.

M4b. Validating the RESAF by comparing the outcomes (results) with other available benchmarks or Saudi Arabian results from previous studies in the literature.

M5 Revising the RESAF beta version based on the feedback and notes obtained during the validation steps 4a and 4b.

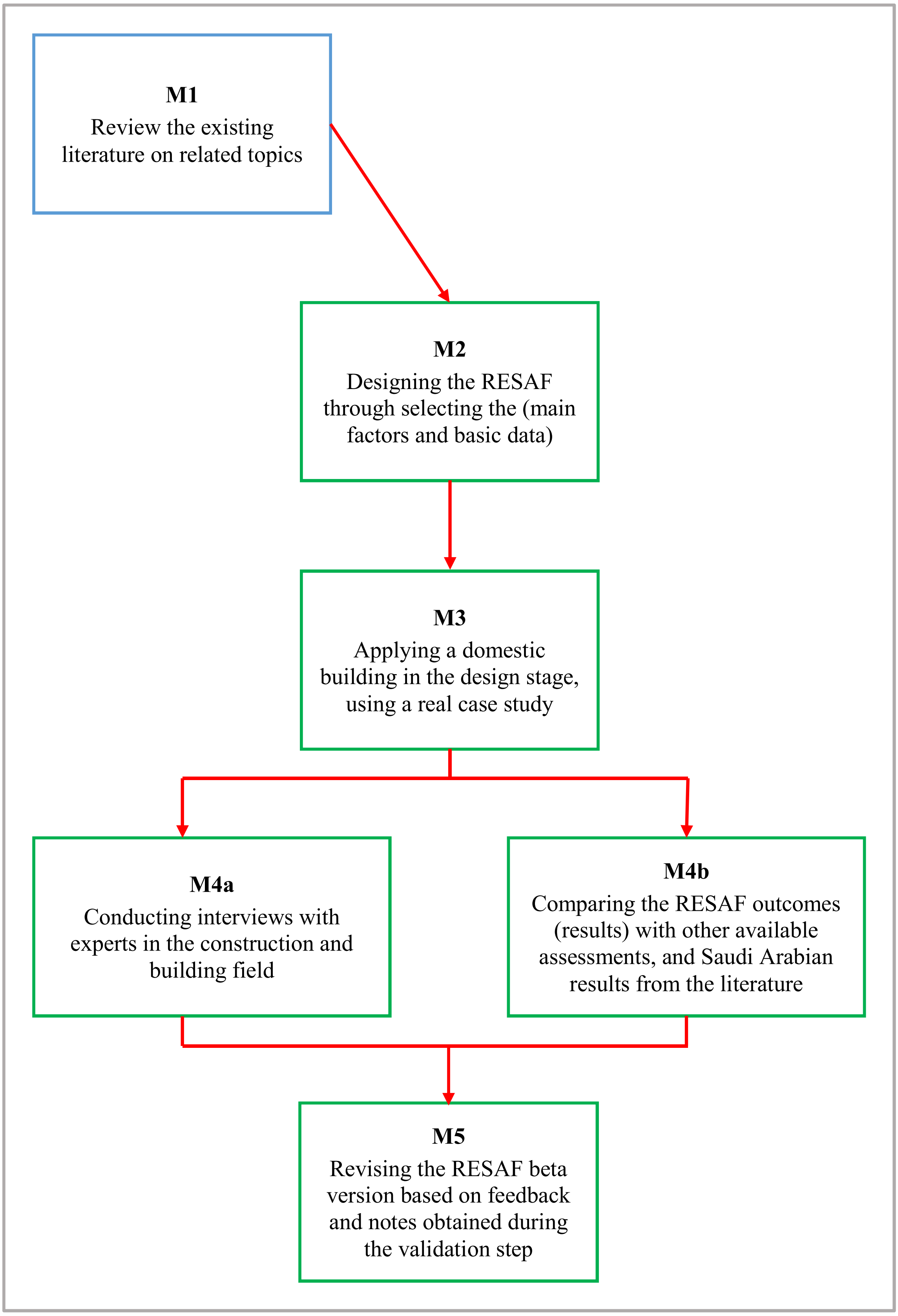


Figure 3-1 Methodology steps chart

Developing such a framework is designed to comply with the seven key points stipulated by Laurentiis (2017). These points are explained in Table 3-1. All of the above points were considered when designing the framework and when creating the user manual. A checklist demonstrating how these points were achieved is presented at the end of Chapter 5 (Results and Discussion).

Table 3-1 Framework general requirements

No	Requirements	Explanations
1	Contextual applicability	The RESAF should be tailored to the local conditions found in the Saudi Arabian building industry, i.e. it must include a wide range of construction materials available in Saudi Arabia.
2	Usability	- In order to help users employ the framework, a user manual should be created. This should include an example of a case study and how the framework was used for the case study. - Potential users are assumed to be engineers and other professionals involved in building construction with average computer literacy skills. The RESAF will be created with a user-friendly interface suitable for this level of computer skills. - In addition, users should only be expected to input data that is readily available to them, as this will ensure that the framework is employed successfully.
3	Meaningfulness	It is important for the users to be able to understand the results of the RESAF. For this reason, the indicators need to be familiar to the users and already employed within the building community.
4	Adequate completeness	RESAF must provide clear assessment procedures for both sustainability and resilience (see Chapter 4).
5	Validity	The validity of the RESAF's results should be tested in the context where it is to be employed, i.e. Saudi Arabia, to ensure that they are relevant to the building industry. The ease of use of the framework will also be verified through interviews with experts in the field.
6	Transparency	The user manual is a key factor in the transparency of the framework, as it will contain information such as the calculation formulas that make it clear how the framework arrives at its results. Other information recorded in the framework, such as the sources of the data, also need to be clearly stated to provide maximum transparency and a way of assessing the credibility of RESAF.
7	Adaptability	It is vital that the RESAF can be adapted as changes occur, for example when new data such as emission coefficients are available. The framework's users may also wish to use their own particular assumptions such as embodied energy figures or carbon from other sources. The framework should be adaptable in this manner.

3.2. Research methods used to conduct the research

This section outlines and explains in general terms the research methods that have been used in the research. Step 1 was completed in Chapter 2.

3.2.1. Step 2: Designing the RESAF

The Resilience and Environmentally Sustainable Assessment Framework RESAF has been developed to help building practitioners (e.g., architects, designers, builders, engineers, contractors) in Saudi Arabia to select appropriate construction materials that meet sustainability (i.e. environmental) and resilience criteria. A framework, consisting of two filters is proposed (Figure 3-2) that can be used to assess the environmental sustainability (inner filter) and resilience performance (outer filter) of building material(s). Passing material choices through both of these filters allows the user to assess a range of materials used within the building during its construction (short term) and over its lifetime (operation for cooling and heating demands). A detailed description of the design of the RESAF is provided in Chapter 4.

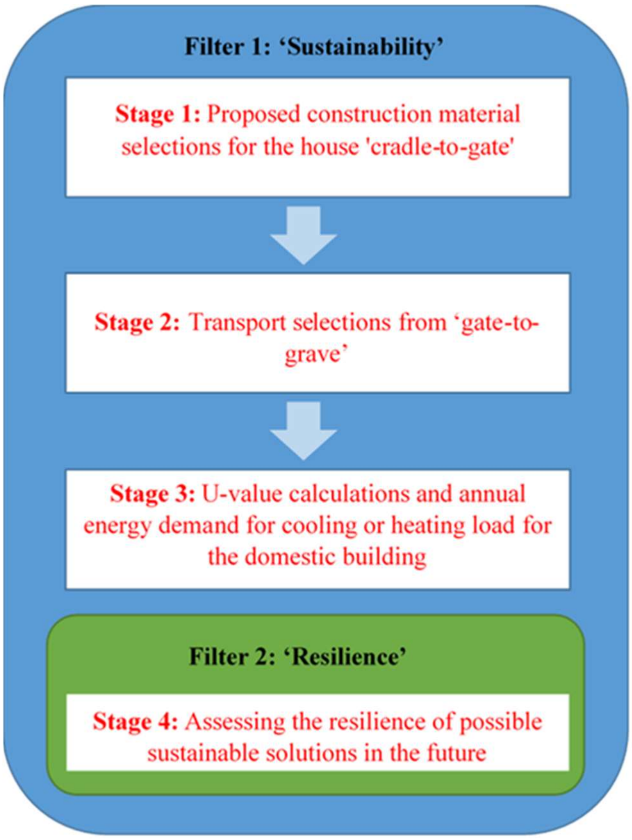


Figure 3-2 RESAF framework filters and steps

3.2.1.1. A. The Inner Sustainability Filter

As stated in Chapter 2, the LCA assessment principles will be employed for designing the framework, but a simplified LCA has been used. This was deemed necessary for practical reasons - because applying a fully compliant LCA takes a great deal of time and resources due to the large amount of primary data needed for the lifecycle inventories (Laurentiis, 2017). Furthermore, Architects and Quantity Surveyors require simple approaches that can be employed without having in-depth knowledge of LCA (Hollberg and Ruth, 2016).

Common ways of simplifying LCA methodologies are decreasing the number of indicators used or the number of building lifecycle phases included (Oregi et al., 2015). To aid interpretation of the results, the impact categories and indicators should be kept simple. For example, few people would understand the result if eutrophication were included as an impact category, but they would understand results given in terms of embodied carbon $kgCO_2e$ and embodied energy kWh_e as they are widely used and well known (Bribián et al, 2009). Bribián et al.'s (2009) simplified LCA methodology as shown in Figure 3-3 provides the methodological approach adopted within the outer 'sustainability' filter of RESAF – noting that environmental sustainability is the focus [Please refer to Chapter 4 – Figure 4-1 for the specific adapted LCA methodology used herein.]

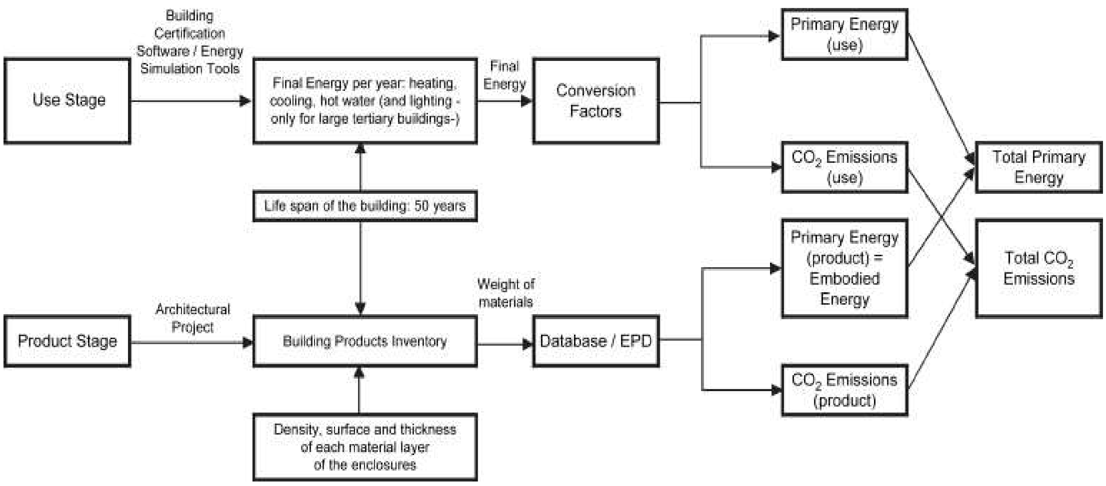


Figure 3-3 Structure of the simplified LCA methodology for 'Environmental sustainability' filter (Bribián et al., 2009)

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RESAF looks to protect and enhance the environment hence the measurement of the material's environmental aspect takes into account ecology, required energy and resources. Attention is given to the concept of 'ecology' to minimise the negative effects on nature through the reduction of pollution resulting from building operations and the use of building materials. This includes minimising the carbon footprint and energy consumption. This filter consists of three stages of assessment for materials used (i.e. cradle-to-gate, gate-to-grave [transport] and U-value calculations). The units of measure used therein are:

- Embodied carbon ($kgCO_2e$);
- Embodied energy (MJ) where 1 MJ = 0.2778 kWh; and
- U-value ($W/m^2.K$).

For example environmentally sustainable measures are used to assess energy (embodied and long-term consumption and carbon embedded and embodied). Criteria can be used to assess as many materials as possible as well as the combining of these materials in format of walls and roofs. The filter allows material choices to be refined and improved as new information emerges within each step. Once the material choices have gone through the inner resilience filter they should be passed through a Resilience Filter (Section 3.2.1.2)

3.2.1.2. B. The Outer Resilience Filter

The inner filter looks at resilience aspects and it is concerned with the long-term impacts of the selected materials and decisions when considering aspects like the local sourcing of materials and the long-term *'bounce-back-ability'* of the building. In other words, the future performance of materials selected in Stages 1, 2 and 3 are considered within the context of three very different future scenarios. These scenarios are considered in the form of a matrix, as described in (Chapter 4, Section 4.3).

3.2.2. Step 3: Applying RESAF to a case study

Once the RESAF is developed, a case study of a domestic building in the country will be applied. This step is mainly concerned with assessing the current design of a building and how it can be improved in terms of the embodied energy and carbon of the materials used, as well as the operation stage of energy consumption for cooling and heating. In order to complete this method in a logical manner, house design plans and details should be available.

The following information is required in order to make an assessment of the domestic building:

- Domestic building plans and dimensions;
- Location of the building;
- Soil types at the location of the building (see Section 4.2.3.3);
- Construction materials (types and quantities);
- Modes of transport and gate-to-grave (from the factory gate to the end of the use of the building) distances (where available);
- Detailing about wall and roof construction; and
- Glazing types (e.g., windows or skylights).

The reason for selecting a design stage is that it is the only opportunity to allow changes to be made to the choice of construction materials. Basbagill et al. (2013) highlighted the fact that the decisions taken during the first stages of a building's design have a large influence on the impact it has on the environment. By applying the framework to a case study we are able to determine which components of a building can improve its sustainability and resilience the most, and therefore these can form the focus of the conceptual design stage (Röck et al., 2018).

The building selected is in Dammam city, and the details of the case study are presented in (Chapter 4, Section 4.5)

3.2.3. Step 4a: Conducting interviews

Seeking information and feedback from individuals about the outcomes of a product or service, existing or proposed, is a form of research (Thiel, 2014). The purpose of these interviews was to assess the validity, relevance and ease of use of the beta version of the RESAF being developed, and also to ask for suggestions on how it might be improved. In addition, the experts' feedback was sought in order to discover any concerns, barriers, solutions or inducements in the implementation of this framework.

Buchbinder (2011) defines a validation interview as a conversation between an interviewer and interviewee that has the aim of verifying or amending the findings of research (in this case, the RESAF). It was very important to consult experts in Saudi Arabia to ensure that the framework is accurate in the Saudi context and local conditions, and that it covers all the needs of the potential users.

Sixty-minute semi-structured interviews with descriptive questions and multiple choice questions were conducted with experts in the field, see Section 4.6.1 for the interview outline (steps) and the time allocated for each step. The reason for this 60-minute duration is Taleb's (2011) suggestion of not exceeding more than 60 minutes for the length of an interview, as interviewees will not be willing to participate for a longer period (the suggestion was made after organising interviews in Saudi Arabia on the topic of housing sustainability). Wilson (2014), following the advice of Weller (1998), recommends starting with general questions and narrowing the focus to more specific questions as the interview proceeds, known as the funnel approach. This is believed to avoid the bias that might occur if the more specific questions were asked first. Therefore, the interview script contained two parts:

- General questions for an overview about the project; and
- Questions for feedback on the framework, including areas for improvement.

Part 'a' provided an overview about the interviewee's background in the subject, as well as assessing the needs of the research project. On the other hand, part 'b' focused on an assessment of the RESAF input and output, how RESAF works, the user manual, possible improvements, and how it could implemented in Saudi Arabia. Each participant was asked the same list of questions, but there were always opportunities to give further explanation or information when necessary. The answers each interviewee provided were recorded based on the participants' preferences: handwritten by the participants (most of them preferred this option) or handwritten by the researcher. They were then transferred to a computer for analysis (see Appendix B for a complete list of the interview questions).

The interviews were carried out face-to-face so that the interviewer could easily clarify questions or points (Tanner, 2018). In this case, this meant explaining about the RESAF and answering any questions posed by the participants. This enabled the researcher to probe for longer gaining more in-depth answers where appropriate by asking more complex questions. For the interviews, it was also taken into account that the interviewees would need to read the user manual and see how the framework had been applied to the case study, so that they were familiar with the RESAF before answering questions on it. Details of how the interviews were conducted, in particular the interview outline and questions, are provided in (Chapter 4, Section 4.6).

A careful consideration of the issues of bias and conflict of interest was made in the interview process. This is to avoid the outcomes of the interview process being invalidated or misinterpreted (Mears, 2009). The following steps were taken:

- There are no friend or colleague relationships between the researcher and the interviewees. Interviewing these people can pose a challenge, as it may affect the interviewees' views versus the researcher's perceptions (Mears, 2009);
- During the interview, the researcher needs to be an active listener and avoid reactions to the interviewees' answers, especially if they presented different views. This is because a researcher is seeking information from interviewees, which does not mean that this information should match the researcher's views (Mears, 2009);
- Anonymity of the interviewees was ensured; this was important so that interviewees could criticise or give their views about current practices in the construction industry (Taleb, 2011), especially the barriers to establishing sustainability and resilience in Saudi Arabia; and
- The interviewees should have experience in the Saudi Arabian context. This is to make sure that the interview outcomes are reflective of the construction industry and regulations in the country. This approach is used by studies that focus on Saudi Arabia's sustainable housing (Taleb, 2011; Aldossary, 2015; Al Surf, 2017).

The selection criteria of the potential interviewees (experts) are outlined in Section 4.6.3. Information about the participants, such as their profession, organisation type, level of education and years of experience, can be found in Table 4-11, Section 4.6.3). Ethical considerations were taken into account and ethical approval was granted by the university.

3.2.4. Step 4b: Comparing the RESAF with literature review

The purpose of this step was to check whether the framework and its outcome (results) were in line with previous studies via a series of comparisons. The studies identified in the literature review were used as a benchmark. Details of how the comparison was performed can be found in Chapter 4, Section 4.7.

3.2.5. Step 5: Revising the RESAF

Based on Step 4, after analysing the interview respondents and comparing the RESAF with previous studies, actions were taken to implement necessary changes into both the RESAF and its accompanying user manual. There is a need to be transparent with regards to where, how and why changes were made. Any changes resulting from the consultation are provided therein (Chapter 5, Section 5.3 to 5.5). A final version of the RESAF (see Electronic copy of the Framework RESAF) and its user manual (see Appendix G) are also provided.

3.3. Summary

This chapter outlined a five-step methodology employed within RESAF - a two filter approach: sustainability followed by resilience). Therein the key contributing elements of a simplified LCA and resilience guide were briefly outlined. Step 1 (a systematic Literature review) was detailed in Chapter 2. The detailed design of the framework (from Steps 2 to 5) is outlined in the following chapter.

4. Development of the framework (RESAF)

4.1. Introduction

This chapter forms the core of this PhD research project. Herein it is detailed how the process of developing RESAF took place and how the current version of the framework was achieved. Most importantly, the chapter specifies the data and calculations underpinning the design of RESAF (beta version). After outlining the case study used to test RESAF, the validation process is described for generation of the final version.

The Excel-based tool that accompanies the framework was developed to facilitate consideration of the environmental impacts associated with domestic building design, and especially the carbon ($kgCO_2e$) and energy (MJ or kWh) implications of changing material choices. This can be downloaded from the following link: https://drive.google.com/drive/folders/1z3jJOhpl-IJdPYcp5JPUnqZo5cw5eu9G - password: 8090 for the final version. As indicated in Figure 3-2 (in previous chapter), the design of RESAF incorporates both sustainability and resilience filters; stages of RESAF are summarised in Table 4-1 below.

Table 4-1 RESAF stages

Filter	Approaches /tools	Stages	Outcome
Sustainability	Simplified LCA Two measures ($kgCO_2e$ and MJ)	(1) Proposed construction material selections for house 'cradle-to-gate'	Materials-embodied carbon and energy
		(2) Transport selections from gate-to-grave	Transportation-embodied carbon
		(3) U-value calculations and annual energy demand for cooling or heating load (domestic building)	In-use energy consumption and carbon footprint
Resilience	Urban Futures Assessment	(4) Future of material choices	Potential of the sustainable materials (solutions) to be implemented within a future three-level scenario (New Sustainability Paradigm, Policy Reform, Market Forces)

4.2. Design of RESAF: Part 1—sustainability filter

The sustainability filter uses a simplified LCA assessment in line with Bribián et al. (2009) as described in Chapter 3 (Figure 3-3). The simplified LCA used herein is shown below in Figure 4-1.

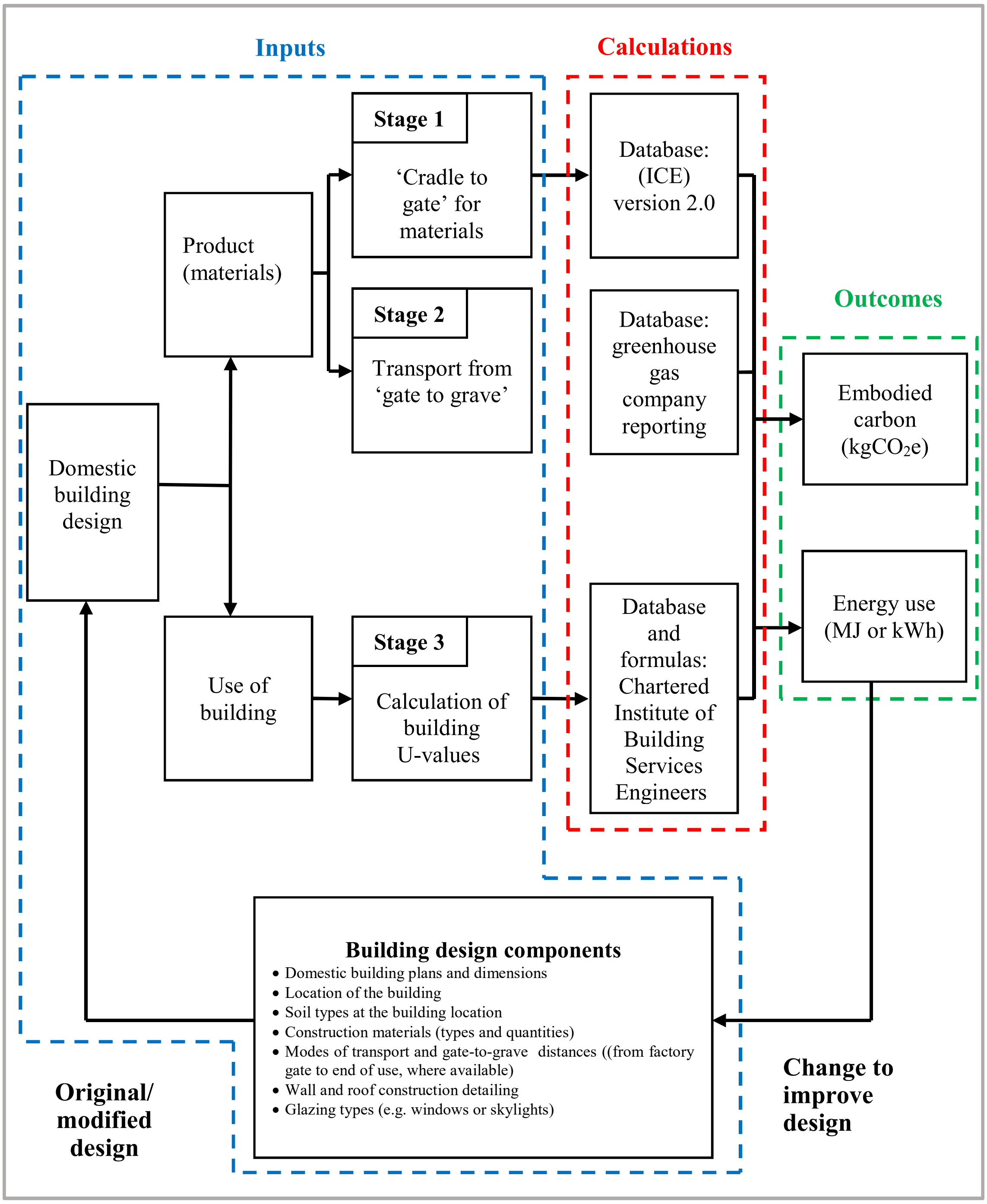


Figure 4-1 LCA structure for RESAF

As indicated, the sustainability assessment filter involves a three-part process (i.e. inputs, calculations and outcomes), which can be repeated until the framework user achieves an acceptable outcome; the reduction of embodied carbon and energy to a pre-defined target. It depends on the house design and the proposed materials, which will be used for building construction [because RESAF user might have multiple construction materials to select from, the user manual (see Appendix G) describes the steps of the selection process].

The key elements are the inputs related to product (i.e. Stages 1 and 2) and building use (i.e. Stage 3). All stages, associated calculations and outcomes are described below.

4.2.1. Stage 1: Proposed construction material selection for a house 'cradle to gate'

At this stage, the embodied carbon and energy from the cradle-to-gate assessment for construction materials are considered. Cradle-to-gate is defined as the life-cycle of the product from the moment the resources are extracted to the time the material is ready for transport to the factory gate (Jacquemin et al., 2012; Moretti et al., 2017). Stage 1 is designed in line with the basic data extracted from the Inventory of Carbon & energy (ICE) version 2.0. (Hammond and Jones, 2011a). The data from this (and previous) versions have been used in a number of studies; therefore, no future validation is needed within the scope of this PhD (Hashemi et al., 2015; Vilches et al., 2017; Kupwade-Patil et al., 2018). In addition to this, data have been organised based on LCA and ISO 14040/44 principles and are in line with the associated framework originally developed by Hammond and Jones in 2011 (see Hammond and Jones, 2011b).

There are 14 categories of construction materials in the framework: aggregate and sand, aluminium, block, carpet, cement, ceramics, ready-mix concrete, precast concrete, glass, insulation, paint, plastics, steel and timber. All these categories include a number of types, making 162 types in total, covering the most important materials which are likely to be used in a domestic property in Saudi Arabia. [It is not inappropriate to assume that many of these construction materials are broadly similar to those found in other regions around the world – the flexibility of the framework allows addition of construction materials to match the regions requirements].

The data used in this stage are based on the Embodied Carbon Coefficient (ECC_{mat}; $kgCO_2e/kg$) and Embodied Energy Coefficient (EEC_{mat}; MJ/kg) of the construction materials. These data are reported in Table 1, Appendix E, as well as on the framework data page.

The Embodied Carbon (EC_{mat}; in $kgCO_2e$) and Embodied Energy (EE_{mat}; in MJ) for the construction materials is calculated by Equation 1a and 1b respectively.

$EC_{mat} = ECC_{mat} \times MQ$	(1a)
$EE_{mat} = EEC_{mat} \times MQ$	(1b)

Where:

MQ = Construction Material Quantities (kg)

The following example illustrates the use of Equation 1: if 4 kg (MQ) of PVC Pipe is used in a building and the associated ECC_{mat} = 3.23 $kgCO_2e$/kg, the

EC_{mat} for this material = 4 x 3.23 = **12.92 $kgCO_2e$.**

4.2.2. Stage 2: Transport selection from gate to grave

In order to improve the scope of embodied carbon $kgCO_2e$ for the construction materials, Stage 2 is included within the framework. *'Freighting goods (downstream)'* and *'well-to-tank (WTT) (upstream)'* data have been taken from Government emission conversion factors for greenhouse gas company reporting (Department for Business Energy & Industrial Strategy, 2018). As per the same points of reference (albeit updated) and the greenhouse gas protocol reported by Ranganathan et al. (2004), freighting goods emissions are caused by fuel use (e.g. diesel or petrol) during transport (e.g. operating a van or ship). [However, it should be noted that the WTT emissions result from fuel production until it reaches the transport modes (e.g. those embodied from extracting and refining crude oil)].

In construction projects, different modes of transport may be used, depending on the types and quantities of construction materials. These modes of transport vary in terms of fuel consumption and carbon footprint (Nadoushani and Akbarnezhad, 2015). Table 2 in Appendix E presents the carbon coefficients for different transport modes based on average loads for each transport mode. Data are reported in $kgCO_2e$/tonne.km and converted to $kgCO_2e$ for each transport mode (i.e. heavy goods vehicle (HGV) diesel, diesel vans, petrol vans, rail, freight flights, cargo ships) as calculated in Equation (2).

$EC_{transp} = ECC_{transp} \times MQ \times D$	(2)

Where:

EC_{transp} = total embodied carbon from transport construction materials ($kgCO_2e$);

ECC_{transp} = Embodied Energy Coefficient for transport mode ($kgCO_2e$/tonne.km) (for freighting goods, WTT or both);

MQ = construction material quantities (tonnes); and

D = transport distance (km).

The following example illustrates the use of Equation (2) to calculate the transport carbon footprint for a given material. If 16 tonnes of material (MQ) is to be delivered to a construction site using a transport mode [HGV Diesel - Rigid (>17 tonnes)] and the distance (D) is 20 km, (Table 2, Appendix E) shows that ECC_{transp} for this mode of transport is 0.22195 $kgCO_2e$/tonne.km, taking account of both freighting goods and WTT; then

$EC_{transp} = ECC_{transp} \times MQ \times D = 0.22195 \times 16 \times 20 =$ **71.02 $kgCO_2e$.**

4.2.3. Stage 3: U-value calculations for domestic building

U-value calculations have been considered in order to help select building materials that reduce the long-term (in-use) energy demand for heating and cooling within domestic buildings (Reilly and Kinnane, 2017).

U-value ($W/m^2.K$) calculations are undertaken for:

a. walls and roof sections,
b. windows and roof light glazing and
c. ground floors.

Therein U-values are converted to gain or loss coefficients ($W\ K^{-1}$). Finally, an annual energy demand and embodied $kgCO_2e$ are calculated for both cooling and heating.

4.2.3.1. *Walls and roof sections*

To calculate the U-value of a construction section, consisting of multiple layers of different material, a simple formulation is used as shown in Equation (3) (Chartered Institute of Building Services Engineers CIBSE (2018).

$U = 1/ (R_{SI} + R_1 + R_2 + \ldots + R_{SE})$	(3)

Where:

U = U-value of individual element (walls and roofs) (W/m^2.K)

R_{SI} = Internal surface resistance (m^{2}KW^{-1})

R_{SE} = External surface resistance (m^{2}KW^{-1})

R_1 and R_2 = Thermal resistance for components of walls and roofs (materials layers) (m^{2}KW^{-1}). Material properties data, including thermal resistance, can be found in Table 3, Appendix E.

It is assumed that the internal surface resistance (R_{SI}) is 0.13 and the external surface resistance (R_{SE}) is 0.04 m^{2}KW^{-1} (Everett, 2018; Santos et al., 2020). These are typical values for heat flow direction (horizontal and ±30°), based on BSI (2017a). A calculation for the thermal resistance of components like R1 is shown in Equation (4)

$R_1 = (d_1 / \lambda_1)$	(4)

Where

d_1 = thickness of material (m)

λ_1 = thermal conductivity (W m^{-1} K^{-1})

Figure 4-2 shows an example of the use of Equations 3 and 4 for a wall specified as Masonry block '1850 kg / m^3', (0.20 m), polystyrene 'extruded' (0.02 m), cement mortar '1650 kg/m^3' (0.02 m). It is assumed that the internal thermal resistance is 0.13 and the external resistance is 0.04 m^{2}KW^{-1} (Everett, 2018).

R1 (masonry block) = (0.20 / 0.90) = 0.222 m^2KW^{-1}

R2 (polystyrene 'extruded') = (0.02 / 0.027) =0.741 m^2KW^{-1}

R3 (cement mortar) = (0.02 / 0.72) = 0.028 m^2KW^{-1}

R_{SI} = 0.13 m^2KW^{-1}

R_{SE} = 0.04 m^2KW^{-1}

Equation 4

U= 1/ (0.13 +0.222 +0.741 +0.028 + 0.04) = 0.862 $W/m^2.K$

Equation 3

Figure 4-2 Example: Equations 3 and 4.

4.2.3.2. Windows and roof light glazing

The glazing U-value for the building depends on several properties (i.e. types of frames adopted, glazing used and gap between panes) and whether it is adopted as a window or roof light. The results for U-values are based on the criteria tables sourced from CIBSE (2018). For glazing U-value criteria, see Table 4, Appendix E. Figure 4-3 shows how the relevant criteria table works.

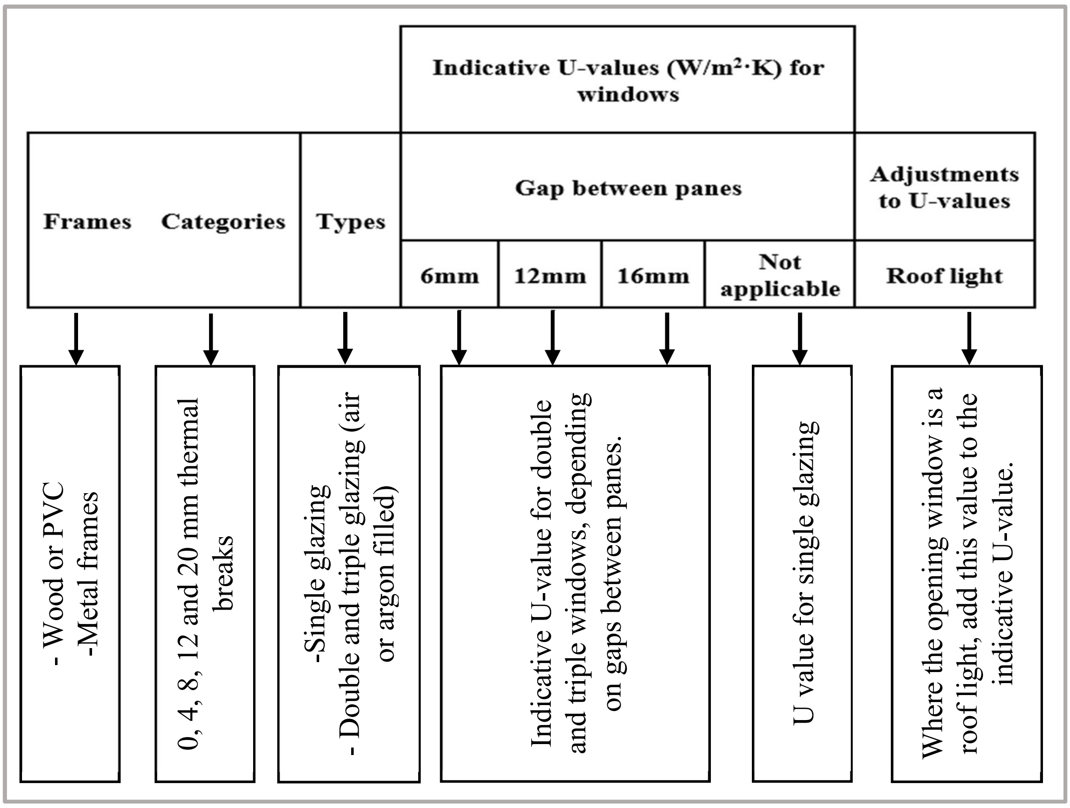


Figure 4-3 U-values criteria for windows

An example of a window properties illustrating how to use the criteria presented in Figure 4-3 follows:

- **Metal frames and an 8 mm thermal break**;
- **Double glazing (low-emissivity (εn) = 0.1; air-filled);** and
- A **6 mm** gap between panes.

See Table 4-2 (the figures in red are used to allocate the figure in green, which is the U-value for the window: **3.1** $W/m^2·K$. If it is a roof light, the U-value is **3.1 + 0.30** = 3.4 $W/m^2·K$.

Table 4-2 Example of criteria for windows

Frames	Types[1]	Indicative U-values ($W/m^2·K$) for windows				Adjustments to U-values
		Gap between panes				
		6mm	12mm	16mm	Not applicable	Roof light
Metal frames (8mm thermal break)	Windows and doors , single-glazed	N/A	N/A	N/A	5.6	0.5
	Double glazing (air filled)	3.6	3.3	3.2	#N/A	0.3
	Double glazing (low-E, ε_n = 0.2, air filled)	3.2	2.7	2.5	#N/A	0.3
	Double glazing (low-E, ε_n = 0.15, air filled)	3.2	2.6	2.4	#N/A	0.3
	Double glazing (low-E, ε_n = 0.1, air filled)	**3.1**	2.5	2.3	#N/A	**0.3**
	Double glazing (low-E, ε_n = 0.05, air filled)	3.1	2.4	2.2	#N/A	0.3
	Double glazing (argon filled)	3.4	3.2	3.1	#N/A	0.3
	Double glazing (low-E, εn = 0.2,argon filled)	2.9	2.5	2.4	#N/A	0.3

[1] Emissivity values are based on coating: soft coating (εn: 0.05–0.1) and hard coating (εn: 0.15–0.2).

4.2.3.3. Ground floors

The ground floor U-value for a building depends on the ground floor area and perimeter as well as the soil type (e.g. clay/silt, sand/gravel, or homogeneous rock) and thermal insulation resistance (m²KW^{-1}). The resulting U-values are once again based on criteria tables sourced from CIBSE (2018). See Table 5 in Appendix E for the U-value criteria for ground floors. Figure 4-4 demonstrates how the relevant criteria table works.

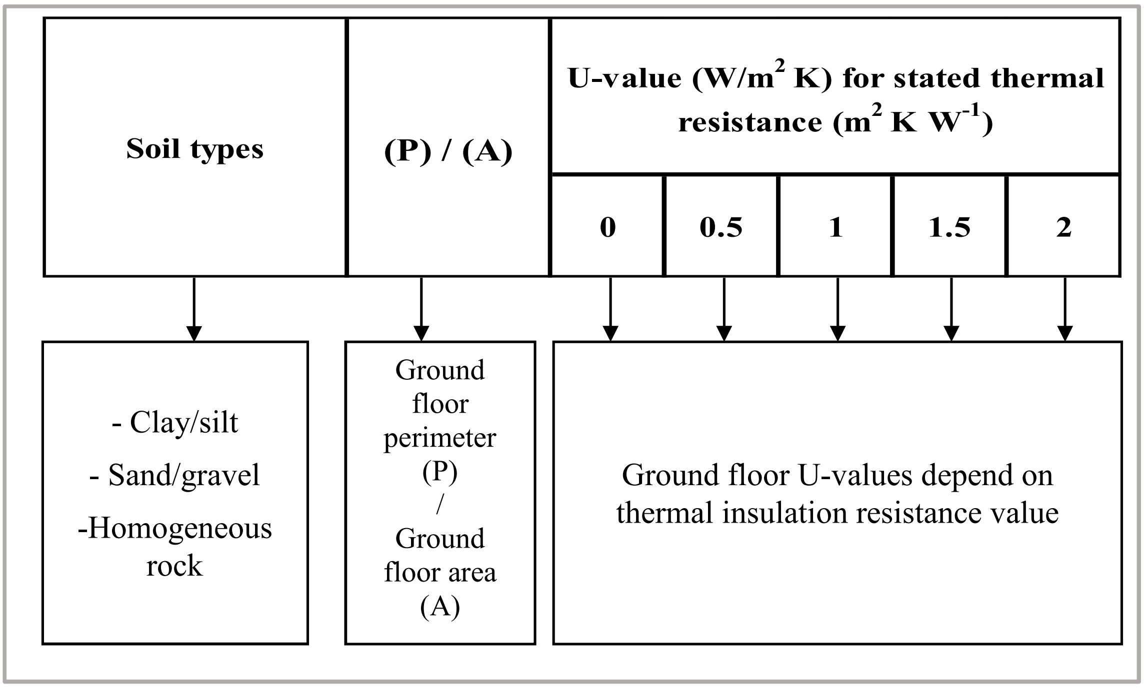


Figure 4-4 U-values criteria for ground floors

An example of a building illustrates how to use the criteria in Figure 4-4:

- Located in **homogenous rock soil;**
- The house perimeter (P) is 40 m, and the area (A) is 100 m^2; therefore, P/A = **0.40**.
- The ground floor insulation type is polystyrene 'extruded'. The thickness (d) is 0.015 m, and the thermal conductivity (λ) is 0.027 W m^{-1} K^{-1}. Applying Equation (4), the thermal insulation resistance (R) is 0.56 rounded to **0.50** m²KW^{-1}.

See Table 4-3, the figures in red are used to allocate the green figure, which is the U-value for the ground floor: **0.72** W/m^2·K.

Table 4-3 An example of the criteria for calculating U-value for the ground floor

Soil types	Ground floor perimeter (P) / Ground floor area (A)	U-value (W/m^2 K) for stated thermal resistance (m^2 K W^{-1})				
		0	0.5	1	1.5	2
Homogeneous rock	0.4	1.16	0.72	0.52	0.43	0.34
	0.45	1.25	0.75	0.53	0.44	0.35
	0.5	1.33	0.78	0.55	0.45	0.35
	0.55	1.4	0.8	0.56	0.46	0.36
	0.6	1.47	0.82	0.58	0.48	0.37

4.2.3.4. Annual consumption (energy demand) for cooling or heating in the building

Equations 5a and 5b are used to calculate the annual energy demand (kWh/yearly) from a building's cooling and / or heating load (Everett, 2018).

$$Q_C = H_t \times CDD \times 24 / 1000 \quad (5a)$$

$$Q_H = H_t \times HDD \times 24 / 1000 \quad (5b)$$

Where:

H_t = Total contribution to the heat gain or loss coefficient of a house from walls, roofs, grounds floors, windows and ventilation) (W K^{-1}) = $H_{t\,(roofs)} + H_{t\,(walls)} + H_{t\,(windows)} + H_{t\,(ground\ floors)} + H_{t\,(ventilation)}$

CDD = Cooling degree-days (°C)

HDD = Heating degree-days (°C)

Q_C = Annual cooling energy demands (kWh/year)

Q_H = Annual heating energy demands (kWh/year)

The data on degree days were extracted from ASHRAE (2017) (see Table 7, Appendix E). Degree days are the total of the differences between the outside temperature and a reference temperature measured over a determined period of time

(Ciulla et al., 2015). A base temperature of 18.3 degrees is used when calculating heating and cooling degree days, this adheres to the Saudi Building Code (Indraganti and Boussaa, 2017). The multiplication by 24 is necessary to convert days into hours and kilowatt-hours (kWh) are obtained by dividing by 1,000.

$H_{t\ (\text{roofs, walls, grounds floors, windows})}$ is calculated from Equation 6:

$H_{t\ (\text{roofs, walls, grounds floors, windows})} = U \times A$	(6)

Where:

U = U-value of individual element (roofs, walls, grounds floors, windows) (W/m^2.K)

A = area of element (m^2).

Note that the contribution of ventilation to the heat gain or loss coefficient (W K^{-1}) is calculated as in Equation 7:

$H_{t\ (\text{ventilation})} = 0.33 \times V \times n$	(7)

Where:

V = volume of the house (m^3)

n = rate of air changes per hour (ACH).

The example in Figure 4-5 applies Equations 5a, 5b, 6 and 7 for a room, where:

- The roof area (A) = 6 m^2 with a U-value of 0.70 W/m^2.K;
- The wall area (A) = 27 m^2 with a U-value of 0.86 W/m^2.K ;
- The window area (A) = 3 m^2 with a U-value of 3.10 W/m^2.K;
- The ground floor (A) = 6 m^2 with a U-value of 0.72 W/m^2.K;
- The room volume (V) = 18 m^3 with an n = 0.50 ACH; and
- Located in Khamis Mushait city, cooling degree-days (CDD) and heating degree-days (HDD) for this city = 1042 °C and 313 °C, respectively (taken from Table 7, Appendix E).

$$H_{t\,(roof)} = U \times A = 0.70 \times 6 = 4.20 \ W\,K^{-1}$$

$$H_{t\,(wall)} = U \times A = 0.86 \times 27 = 23.22 \ W\,K^{-1}$$

$$H_{t\,(window)} = U \times A = 3.10 \times 3 = 9.30 \ W\,K^{-1}$$

$$H_{t\,(ground\ floor)} = U \times A = 0.72 \times 6 = 4.32 \ W\,K^{-1}$$

Equation 6

$$H_{t\,(ventilation)} = 0.33 \times V \times n = 0.33 \times 18 \times 0.50 = 2.97 \ W\,K^{-1}$$

Equation 7

$$H_t = H_{t\,(roofs)} + H_{t\,(walls)} + H_{t\,(windows)} + H_{t\,(ground\ floors)} + H_{t\,(ventilation)} = 4.20 + 23.22 + 9.30 + 4.32 + 2.97 = 44.01 \ W\,K^{-1}$$

Annual cooling energy demands (Qc) = Ht x CDD x 24 /1000
= 44.01 x 1042 x 24 / 1000
= 1101 kWh / yearly

Equation 5a

Annual heating energy demands (Qh) = Ht x HDD x 24 /1000
= 44.01 x 313 x 24 / 1000
= 331 kWh / yearly

Equation 5b

Figure 4-5 Energy demand equations example

4.3. Design of RESAF: Part 2—resilience filter

Today it should not be unusual for building designs to incorporate considerations of sustainability and resilience (in addition to adaptability and liveability) (Rogers, 2018). As reported by Rogers (2018), civil engineers must be provided with support to improve how their interventions (in this case materials) are conceived, prepared and implemented so that they align with these concepts and are able to adapt to changing circumstances in the future.

With Environmental sustainability of material selection having been assessed in Filter 1 the assessment of resilience is undertaken in Filter 2. This secondary filtering process is based upon an *'Urban Futures assessment'* of the future performance of materials selected in Stages 1, 2 and 3 (i.e. outcome of Filter 1 process) in the context of three distinct future scenario archetypes (see Raskin et al, 2002; Hunt et al, 2012). See Section 6.4 for the limitations of the research (not using more than three scenarios).

- **Scenario 1.** *Market Forces (MF)*; a conventional scenario sometimes referred to as business-as-usual, where no major changes to current patterns of behaviour are expected. In terms of material selection this would likely mean that sustainability does not feature high up the agenda and the aesthetics (i.e. form) and function of a material waste is considered far more readily than sustainability credentials.
- **Scenario 2.** *Policy Reform (PR)*; based on strict policy to achieve sustainability goals. In terms of material choice sustainability is likely to feature much higher on the agenda enforced by strict policies for improving material selection.
- **Scenario 3**. *New Sustainability Paradigm (NSP)*; it is led by the widely accepted sustainable citizen values and behaviour. For material selection it is likely that citizens readily embrace sustainable material choice and the governance systems support such implementation.

In order to do this a number of necessary conditions - NC's (Conditions necessary to allow selected materials to deliver their function in the long term) should be derived (Lombardi et al., 2012). These are shown in Table 4-4.

Table 4-4 Necessary conditions for materials used in domestic buildings

No	Necessary conditions
1	Availability of proposed materials
2	Bounce back ability of the building
3	Absence of other environmental considerations
4	Minimum building code requirements
5	Environmental footprint of transport
6	Public acceptance of sustainable solutions

Table 4-5 An example Resilience Matrix for assessing materials (modified from Lombardi et al., 2012)

Necessary conditions[1]	New Sustainability Paradigm	Policy Reform	Market Forces
(A)	"Green"	"Green"	"Green"
(B)	"Green"	"Green"	"Amber"
(C)	"Red"	"Amber"	"Red"

[1] Letters (A, B and C) are used as examples of necessary conditions to show how the assessment is performed

The matrix in Table 4-5 is used to evaluate the necessary conditions for the sustainable solution (selected materials) regarding their performance in three future scenarios. This evaluation is to decide whether these solutions should be implemented, adapted or replaced by other solutions which will go through the evaluation process again (Lombardi et al., 2012). In each of these future scenarios, there are three grade levels to assess respecting necessary conditions. They are as follows:

- Green. A condition highly likely to continue in the future;
- Amber. A condition at risk in the future;
- Red. A condition highly unlikely to continue in the future.

If green grade has been allocated in all three scenarios, such as condition (A), there is the possibility that this solution (the proposed material choice) can be utilised with confidence. However, if amber or red grades are allocated to one of the three future scenarios, such as conditions (B) and (C), for example, it simply means that the proposed solution is not fully resilient in the case of condition (B) and not resilient at all in the case of condition (C). Both require more research for the possibility of the adaptation or conceptualization of other alternative (more resilient) solution(s) (note that accepting the highlighted risks might be possible in condition (B) but not in condition (C)).

In brief, using a resilience filter and matrix in this way is like brainstorming the future-proof-ability of the proposed solution. For example, when a government body introduces a new policy that enforces use of a particular construction material, this policy may not be implemented correctly in practice because the market may be unable to supply enough of this material to meet demand.

4.4. User manual for RESAF

A user manual explains RESAF functioning and guides its use in the same way as training, with detailed explanations and examples. Figure 4-6 shows a simplified outline of the RESAF user manual, which comprises two sections. The first section is effectively an induction session prior to using the framework, summarising the purpose of the framework as well as information about requirements. The second part shows how the framework is actually implemented—for example, how to complete the forms—and explains the outcomes. A case study tutorial ensures that potential users fully understand how the case study will be implemented and what is expected (in terms of outcomes) when using the framework.

To support the user, calculations and databases are explained, and a reference list is also provided. A user manual can be found in Appendix F for (beta version) and Appendix G for final version.

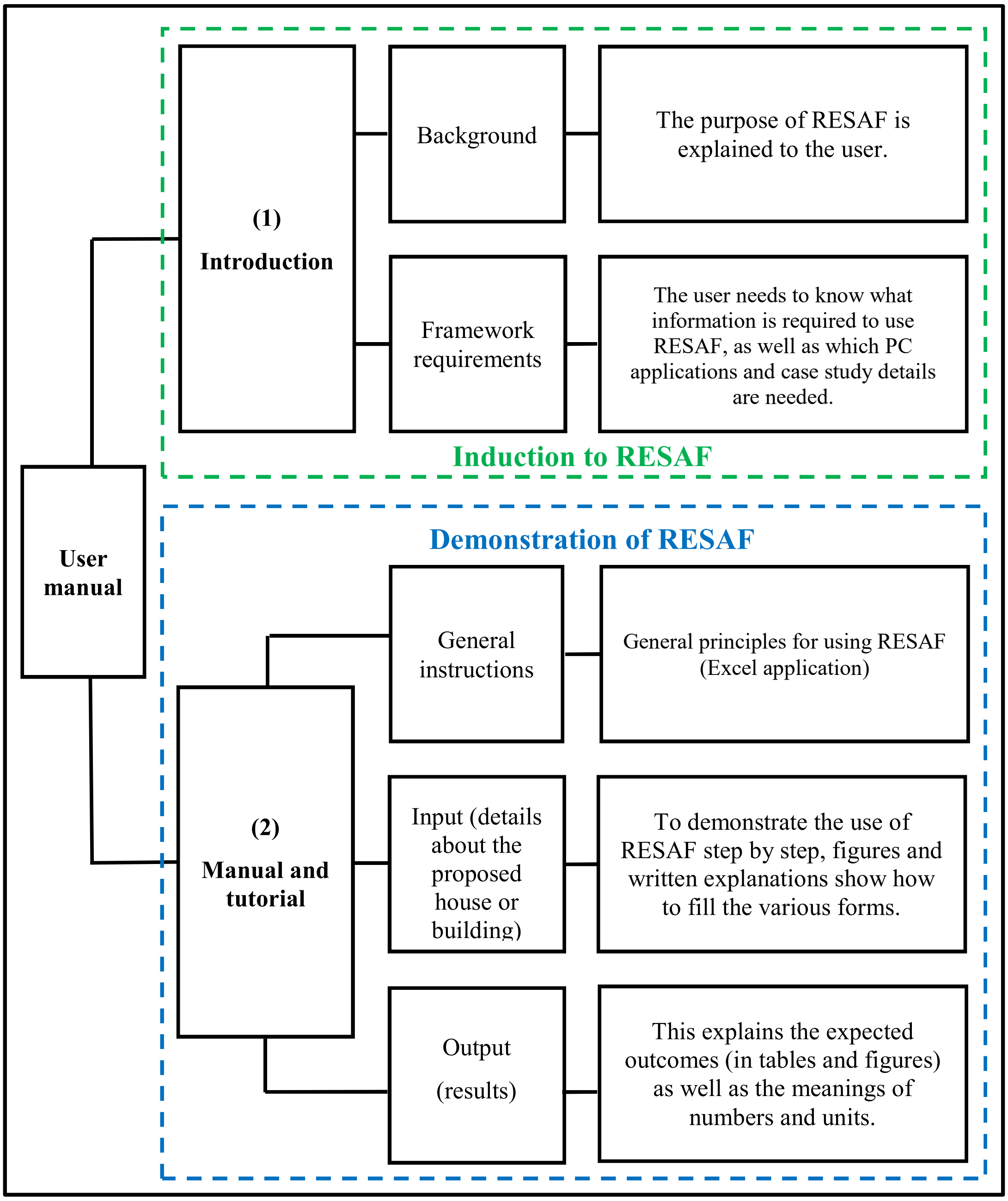


Figure 4-6 User manual: Outline and purpose

4.5. Outline of case study

The building information required to use RESAF was presented in Section 3.2.2. Figure 4-7 explains how the case study design information is managed.

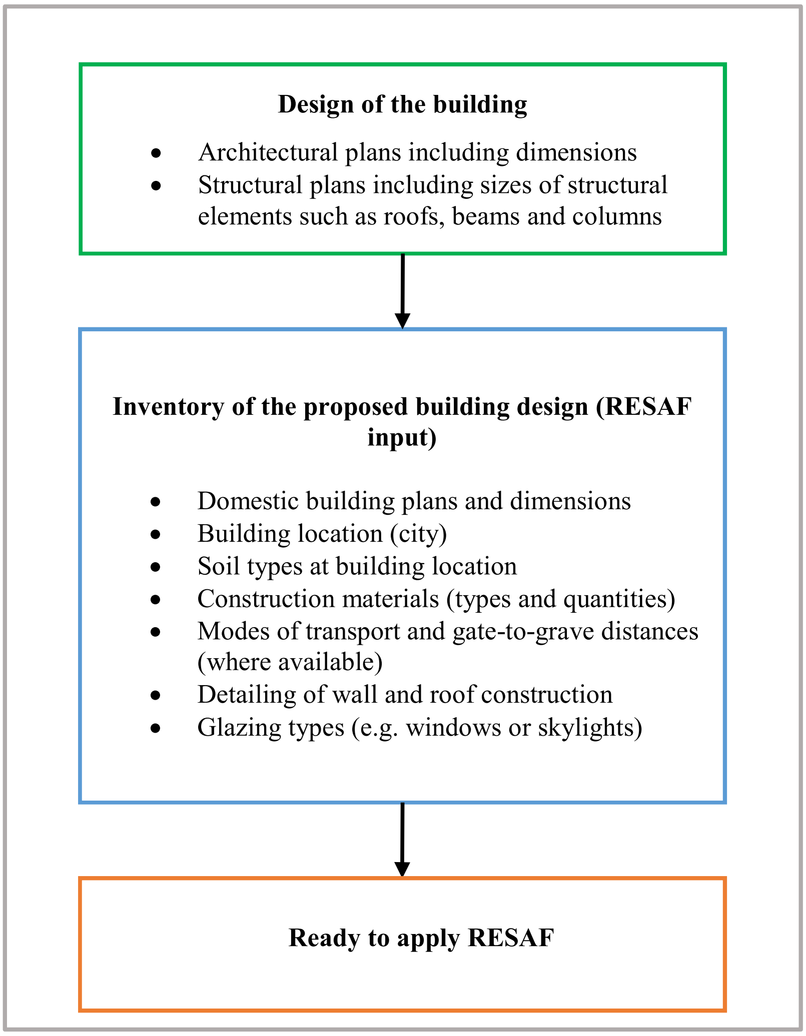


Figure 4-7 Proposed building design for RESAF application

After designing the building, the designer (or framework user) completes an inventory of the proposed design and submits the information required (input). On that basis, the proposed design can be implemented in RESAF.

It may be possible to utilise the framework even when some of the above information is not available. In such cases, appropriate assumptions must be made, supported by appropriate justification. The accuracy and efficiency of outcomes (i.e. results) depends on the availability of the above information as well as on the choices made by users when implementing the framework.

4.5.1. *Housing mix in Saudi Arabia*

In Saudi Arabia, housing buildings can be divided into three types: villa, apartment and traditional house (General Authority for Statistics, 2019b). These are described in the following.

4.5.1.1. *Villa*

This type is a detached or semi-detached building surrounded by fences, forming an individual housing unit (Alzamil, 2014); see Figure 4-8. In Saudi Arabia, the total floor built area of a villa depends on the house land (plot) area (Alrashed, 2015). The assumption is that the total floor built area is equal to 1.50 × the land area, which is based on the current regulations in the country (Bahammam and Haidar, 2020). In Saudi Arabia, the range of land areas is from 450 m^2 to 625 m^2 (Haidar and Bahammam, 2021); consequently, the villa total floor built area ranges from 675 m^2 to 937.5 m2. The majority of land areas in the country are 625 m^2 in size (Aldossary, 2015; Taleb, 2011), which means that a typical villa is approximately 937.5 m^2 (the total built floor area for the current case study is 890 m^2 (see Table 4-7), which means it is a representative villa in the country). Almehrej (2015) indicated the villa height is two floors and a penthouse floor with a 12 m height to the roof floor finishing level. Therefore, the selected villa is in line with this, as the vertical section shows a 12.45 m height to the roof finishing level; see Figure 4-12. Notably, there are concerns with respect to a larger villa size in Saudi Arabia, which is due to the following reasons:

- The land area for the house is huge (Haidar and Bahammam, 2021); the majority area of the land is 625 m^2 for each house building (Aldossary, 2015; Taleb, 2011). This encourages house owners to build larger-sized houses (Aldossary, 2015).
- The villa type usually includes repeated rooms (Ghabra, 2017). For example, it includes separate men and women receptions, which is related to privacy considerations made in the house design (Al Surf, 2017; Mulliner and Algrnas, 2018);
- The number of house occupiers plays a vital role in the size of the house (Al Surf, 2017). The average number of family members per household in Saudi Arabia is 6.7 (Alqahtany and Mohanna, 2019).

- Designers do not consider house occupiers' accurate needs in terms of area and room function in the house (Haidar and Alzamil, 2019). This results in area wastage in the house. An example is designing a bedroom for two people, but in reality, there will be just one person using this bedroom.

A recent study by Haidar and Bahammam (2021) proposed that housing land should be reduced by 50%, which will also result in the house size being reduced by 50% (in Section 5.2.4.2, this option of reducing the size of the case study will be discussed when using RESAF).

Figure 4-8 Villa house type, Saudi Arabian example (Almehrej, 2015)

4.5.1.2. Apartment

An apartment is a group of rooms (i.e. two or three bedrooms, toilets, kitchen, lounge and dining room) forming a housing unit. This unit is located in a multi-story building amongst others units (Alzamil, 2014). Taleb (2011) presented a building floor plan that includes two typical apartments in Saudi Arabia (see Figure 4-9). The area of each apartment is approximately 210 m^2.

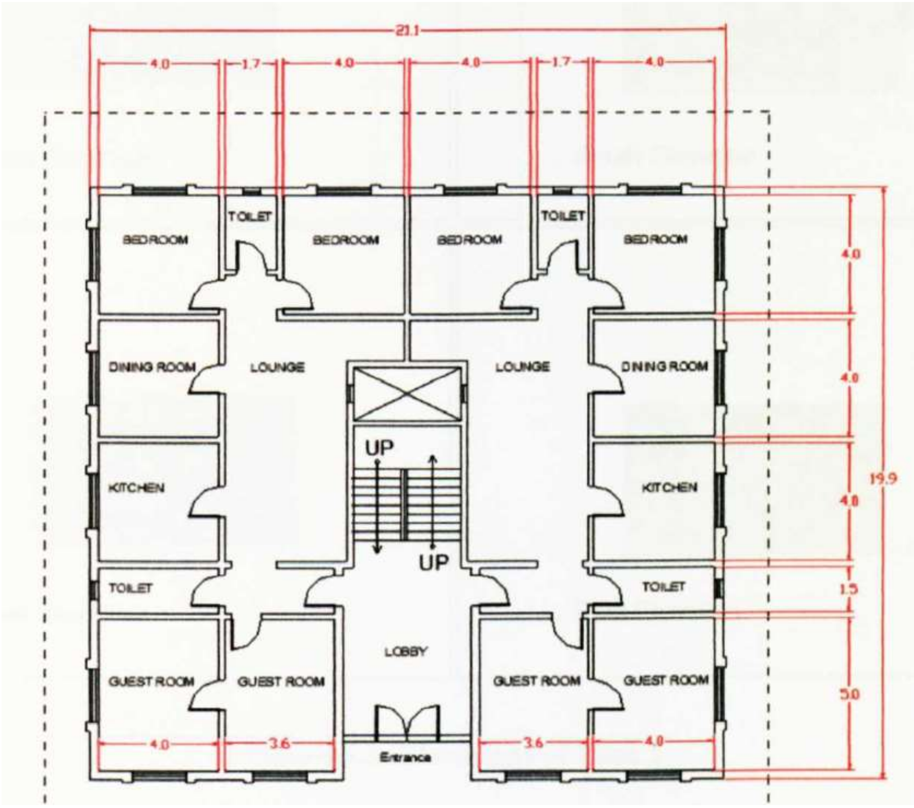


Figure 4-9 Typical floor plan including two apartments (Taleb, 2011)

4.5.1.3. Traditional houses

Traditional houses were built decades ago and are usually found in rural areas, small towns, old city centres and slums (Alqahtany and Mohanna, 2019; Alzamil, 2014). This type covers 100% of the land area (Alrashed, 2015); usually, there is a courtyard in the middle of the house surrounded by the rooms (Bahammam, 1998). According to Alzamil (2014), the number of this type of housing unit is decreasing. Therefore, these housing units do not reflect contemporary housing in Saudi Arabia.

Table 4-6 shows the number of housing units for each type (villa, apartment and traditional house) occupied by Saudi Arabian citizens. The apartment type has the highest percentage (43.74% of the total units). However, based on several studies, the villa type is the most preferred one in Saudi Arabia (Alzamil, 2014; Alhubashi and Cladera, 2016; Alqahtany and Mohanna, 2019). The reason is that apartments are considered a temporary rented accommodation, such as for new families (Alzamil, 2014). This also explains why this current study used the villa type as a representative housing example in the country.

Table 4-6 Number of units of housing types in Saudi Arabia (General Authority for Statistics, 2019b)

Housing Type	**Traditional House**	**Villa**	**A Floor in a Villa**	**A Floor in Traditional House**	**Apartment**	**Total**
Number of units	664,991	1,095,237	284,088	27,203	1,610,408	3,681,927
%	18.06	29.75	7.72	0.74	43.74	100

4.5.2. Case study information

The case project is a design proposal for a single-family typical house (villa type) to be built in Dammam, Saudi Arabia (see Figure 4-10). The city of Dammam has been selected for the following reasons. First, a single-family house in Dammam is similar to other houses located in other Saudi Arabian cities; in other words, there are no considerable differences in terms of house characteristics (design) (Mohanna and Alqahtany, 2019). The second reason is the economic importance of Dammam, as it is named the *'oil capital of Saudi Arabia'*; the headquarters of the Saudi Arabian Oil Company is located near the city (Alqahtany and Abubakar, 2020). Third, Dammam is the third largest city in the country in terms of area (Al-Shihri, 2016).

Figure 4-10 Map of the Saudi Arabian cities (Modified from Google Maps, 2020)

The total floor area of the house design is 890 m^2 (Figure 4-11 to Figure 4-14). Comprising three floors (see Table 4-7), the concrete structure employs a two-way ribbed slab system. The construction materials are specified in the design proposal, and materials, quantities and specifications are summarized in Table 4-8 in line with the design plans. The total weight of materials is approximately **3,317,715 kg**. This case study is further explored to evaluate the outcome of the dual filtering process (i.e. Environmental sustainability and resilience aspects of material choices) in Chapter 5.

Table 4-7 Proposed house: Floors

Floors	Built Area (m^2)	Purpose	Plans[1]
Ground	381	Visitors' reception and main kitchen	Figure 4-11
First	380	Family living	Figure 4-12
Penthouse	129	Service floor	Figure 4-13

[1]See Figure 4-14 for floor heights.

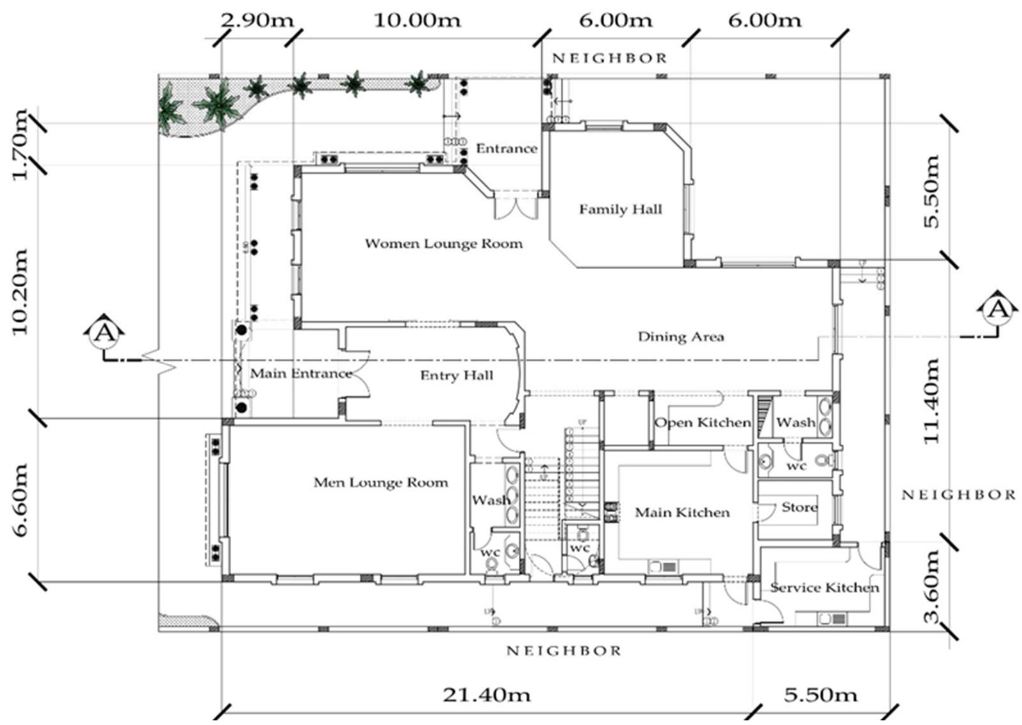


Figure 4-11 Ground floor plans for the domestic building

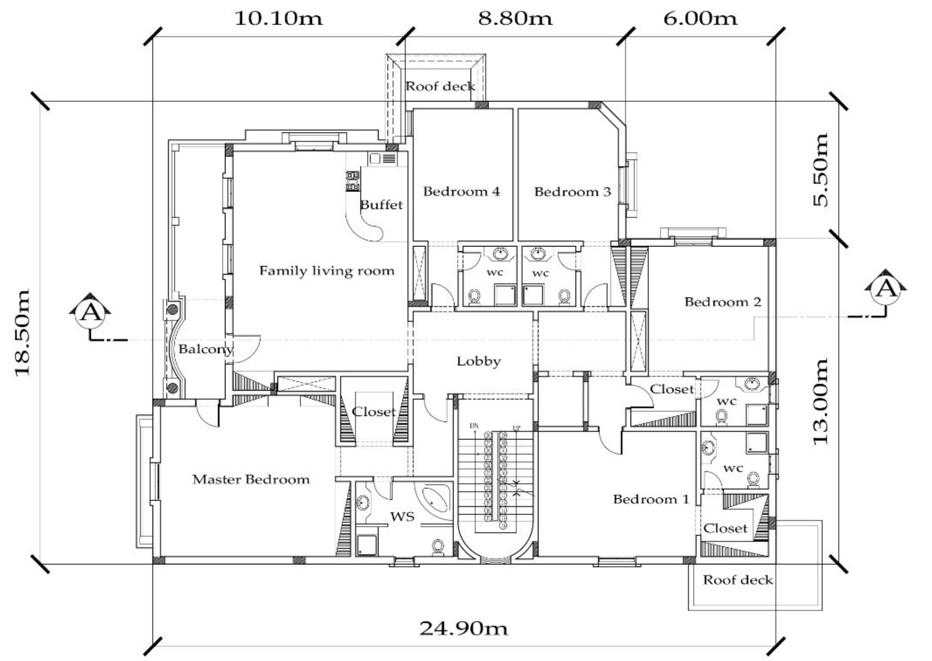


Figure 4-12 First floor plan

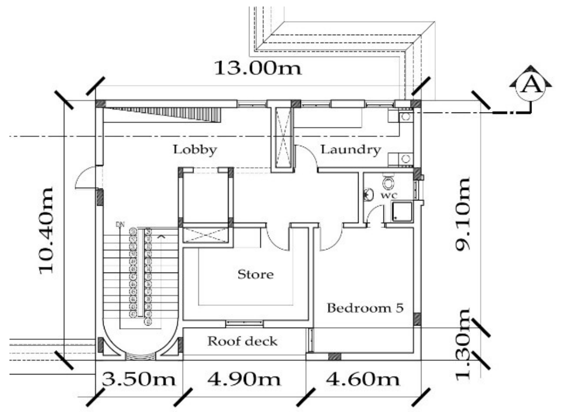


Figure 4-13 Penthouse floor plan

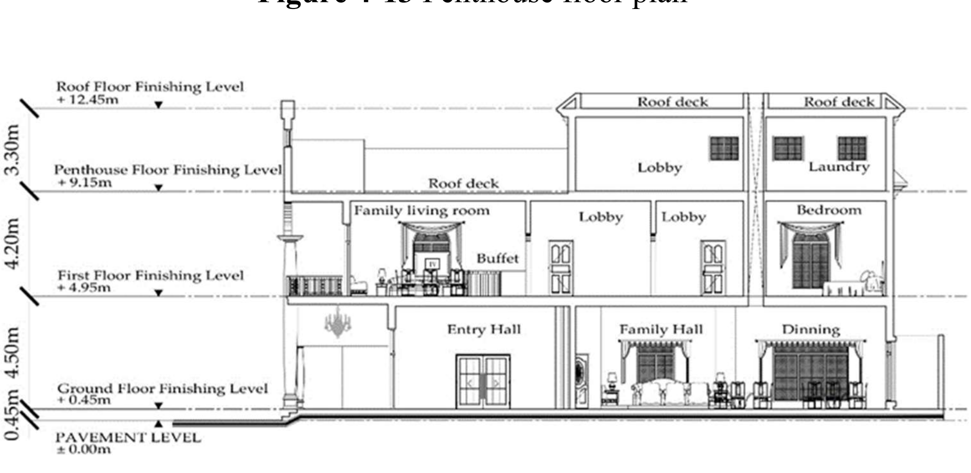


Figure 4-14 Vertical section (A-A) and floors level

Table 4-8 Proposed construction materials in the domestic building design

Material	Type	Quantity (Unit)	Quantity (Kg)	Specifications and Purpose
Ready mix concrete	(25-30 MPa) - 100% Portland cement (CEM I)	31.57 m^3	76,084	Plain concrete for blinding (below foundations, ground beams)
Ready mix concrete	(28-35 MPa) - 100% Portland cement (CEM I)	772.79 m^3	1,870,152	Reinforced concrete for foundations, beams, columns, slabs and stairs
Cement	Mortar (1:3 cement: sand mix)[1]	130.13 m^3	247,247	Top-of-floor slab to receive finishes, concrete blocks insulation and plastering for exterior and internal walls
Steel	Reinforcement steel[1]	-	37,912	Steel rebar for concrete structure elements
Timber	Plywood[1]	3,923.83 m^2	32,960	Formworks in construction process for concrete structure elements
Precast concrete	(25-30 MPa) - 100% Portland cement (CEM I)	5.76 m^2	2,082	Exterior wall cladding
Block	Autoclaved aerated block	7,335 pieces	88,020	Filling the empty spaces in the two-way ribbed slabs
Block	Concrete block: (12 MPa)	2,819 pieces	95,846	Masonry solid blocks for foundation walls
Block	Concrete block: (8 MPa)	27,226 pieces	787,160	Masonry hollow blocks for external and internal walls
Insulation	Expanded Polystyrene[2]	16.61 m^3	531.52	Thermal insulation
Soil[3]	General Aggregate[1]	16.61 m^3	37,206	Roof deck
Timber	Laminated veneer lumber[2]	3.52 m^3	2,816	Doors
Glass	Toughened glass[2]	1.06 m^3	2,650	Windows
Aluminium	General Aluminium[1,2]	1.79 m^3	4,833	Window framing and doors
Carpet	Wool	105.86 m^2	253	Flooring
Stone[3]	Granite[1]	426.72 m^2	7,373	Building facade stone finish
Paint	General paint[2]	3,331.93 m^2	337	Internal and external walls
Plastics	PVC Pipe[1]	1,736.70 m	2,417	Plumbing and electrical pipes
Ceramic	General ceramic[1]	-	8,499	Floors, walls and skirting tiles
Stone[3]	Marble tiles[1]	-	13,344	Floors, walls and skirting tiles
Total			3,317,715	

[1,2] Density of the materials extracted from Asif et al. (2017) and CIBSE (2018) to calculate with kg
[3] These materials are categorized under 'Aggregate and Sand'

4.6. Framework (RESAF) validation: Part 1—interview process

As stated in Section 3.2.3 the feedback interview is part of the process of validating RESAF to gain an overview of the developed beta version. The interview outline, questions and participants are described below.

4.6.1. Interview outline

The sixty-minute face-to-face interview was structured as follows.

- *Step 1* (10 minutes): In line with the university's ethical requirements, each participant was given time to read the participant information sheet and sign the consent form.
- *Step 2* (10 minutes): The student researcher presented the beta version of the RESAF, explaining how it works in terms of its application and outcome.
- *Step 3* (15 minutes): The participant was given time to read the user's manual before using the beta version of RESAF. The purpose of this step is to allow participants to become familiar with the framework and how to use it, as well as identifying likely input requirements and deliverable outputs.
- *Step 4* (25 minutes): Based on Steps 2 and 3, the participant provided feedback about the proposed framework under two headings:
  a) feedback on the project; and
  b) feedback on the framework, including areas for improvement.

This process enabled each participant to practise the RESAF, so maximising the benefits of feedback. Although most interviews lasted an hour as planned, some exceeded two hours because of the interviewee's interests and level of expertise. Participants were allowed to explain or elaborate on their answers and selections where necessary.

4.6.2. Interview questions

4.6.2.1. Feedback on the project

To gain an overview and to understand the participants' background, the following general questions were asked about definitions of sustainability and resilience, using participants' assessments and grading the sustainability and resilience of Saudi Arabian domestic buildings.

A. How would you define sustainability?

B. How would you define resilience?

C. Are there links between sustainability and resilience?
☐Yes
☐ No
☐ I do not know
☐ I do not want to say

D. Do you use any sustainability or resilience assessment tools?
☐ Yes
☐ No
☐ I do not know
☐ I do not want to say

E. How important do you grade each following statement (see Table 4-9). Note: consider each statement independently.

Table 4-9 Importance of statements about Saudi Arabian context

Statements	**Most important**	**Important**	**Slightly Important**	**Not important**	**I do not know**
Implementing **sustainability** concepts in Saudi Arabian residential buildings.	☐	☐	☐	☐	☐
Implementing **resilience** concepts in Saudi Arabian residential buildings.	☐	☐	☐	☐	☐
Implementing both **sustainability and resilience** concepts in Saudi Arabian residential buildings.	☐	☐	☐	☐	☐
The selection of structural materials will contribute to **sustainability**.	☐	☐	☐	☐	☐
The selection of structural materials will contribute to **resilience**.	☐	☐	☐	☐	☐

The selection of structural materials will contribute to both **sustainability and resilience**.	☐	☐	☐	☐	☐
Saudi Arabia establishing their own assessment for **sustainability**.	☐	☐	☐	☐	☐
Saudi Arabia establishing their own assessment for **resilience**.	☐	☐	☐	☐	☐
Saudi Arabia establishing their own assessment for both **sustainability and resilience**.	☐	☐	☐	☐	☐

F. Saudi Arabia needs to customise assessment procedures for sustainability and resilience due their own context and local conditions.

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

G. There are barriers to establishing sustainability and resilience in Saudi Arabia residential buildings.

☐ Strongly Agree
☐ Agree
☐ Neutral
☐ Disagree
☐ Strongly Disagree

4.6.2.2. Feedback on the framework

The following specific questions about RESAF and the user manual sought to determine whether it is easy to use; whether there is any missing information; whether the data are sufficiently accurate for Saudi Arabia; whether the outputs are appropriate and sufficient; and whether the framework is applicable to the Saudi Arabian context and local conditions.

A. Grade your agreement with each following statement about the Resilience and Environmentally Sustainable Assessment Framework RESAF for structural materials in domestic buildings (beta version application) (see Table 4-10) :

Table 4-10 Grade of statements about RESAF

Statements	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The user's manual is considered easy to comprehend and follow.	☐	☐	☐	☐	☐
As 'user', I clearly understand how to use the RESAF confidently.	☐	☐	☐	☐	☐
The RESAF front-page **(input part)** in general, is well presented and clear.	☐	☐	☐	☐	☐
It was easy to fill and select all the forms in the RESAF front-page ***(input / embodied part)***.	☐	☐	☐	☐	☐
It was easy to fill and select all the forms in the RESAF front-page ***(input part / U-value part and annual consumption (energy demand) for cooling or heating load)***.	☐	☐	☐	☐	☐
It was easy to fill and select all the forms in the RESAF front-page (**input part / resilience**).	☐	☐	☐	☐	☐
The front-page **(output part / tables result)** is well presented and clear.	☐	☐	☐	☐	☐
The front-page **(output part – figures result)** is well presented and clear.	☐	☐	☐	☐	☐

It was helpful that the user can get access to (and edit / amend) the database and references list in the background-page.	☐	☐	☐	☐	☐
Based on your experience the result provides an accurate representation (in general).	☐	☐	☐	☐	☐
Based on your experience the **(embodied carbon)** result provides an accurate representation (in general)	☐	☐	☐	☐	☐
Based on your experience the **(embodied energy)** result provides an accurate representation (in general)	☐	☐	☐	☐	☐
Based on your experience the **(U-value and annual consumption "energy demand" for cooling or heating load)** result provides an accurate representation (in general)	☐	☐	☐	☐	☐
Based on your experience the **(cost)** result provides an accurate representation (in general)	☐	☐	☐	☐	☐
Based on your experience the **(resilience)** result provides an accurate representation (in general)	☐	☐	☐	☐	☐

B. By using the framework, are there any missing information (please consider the database, input filling or results)? Please give details of the missing information if you answer [yes]?

☐ Yes
☐ No
☐ I do not know
☐ I do not want to say

C. Database for ‘embodied carbon’, ‘embodied energy’ and ‘thermal conductivity' were extracted from references not considering Saudi Arabia directly. Do you have or know of any suggested references that consider Saudi Arabia more directly? Please list the references if you answer [Yes]?

 Yes
 No
 I do not know
 I do not want to say

D. Would you use the framework proposed in your work?

 Yes
 No
 I do not know
 I do not want to say

Chapter 5 describes the interview responses, results and analysis, as well as explaining and justifying any amendments to RESAF.

4.6.3. Interview participants

The selection criteria to participate in the interview process is based on the respondents’ expertise in the following:

- The domestic building sector in Saudi Arabia, whether in the design, construction or research fields
- Background/interest in sustainability topics on buildings (energy and construction materials), especially in relation to domestic buildings
- Representing a variety of organisation types (consultant offices, construction companies, the education sector, the government sector or semi-government organisations)

Invitations to participate in the interview process were sent to 50 potential interviewees (experts). They were approached via email, telephone or social network (particularly Twitter, as it is commonly used in Saudi Arabia). A total of 44% (22 of 50) accepted the invitation, and the rest did not respond to the request, apologised for not participating (stating, for example, that they are not available) or initially agreed to participate but did not contact the researcher to schedule a meeting. In light of the participants’ extensive experience in the field, especially in relation to domestic buildings and sustainability, the response rate was considered appropriate and acceptable.

See Table 4-11 for the list and details of the participants, including their profession (role), organisation type, level of education and years of experience. The participants' roles represent different professions: engineer, architect, sustainability consultant, manager, planner, urban designer and academic. They also worked in different organisation types: 13 participants in consultant (design) offices, 5 participants in the education sector, 3 participants in a construction company, 3 participants in the government sector (municipality), 2 participants in semi-government organisations and 1 participant in the private sector (note that some participants are involved in more than one organisation type/role, such as participant 7; see Table 4-11). The level of education of the participants was as follows: 9 participants had a bachelor's degree, 6 had a master's degree and 7 had a PhD degree. They also have a range of experiences: 3 participants had 3–5 years of experience, 6 participants had 6–10 years of experience, 8 participants had 11–15 years of experience and 5 participants had more than 25 years of experience. This diversity of perspectives will help refine the framework and make it as effective and user friendly as possible.

Table 4-11 Validation interviews: List of participants

Participant No.	Profession (Role)	Organisation Type	Level of Education	Years of Experience
1	Office manager (Architectural engineer)	Consultant office Construction company	Bachelor's degree	27
2	CEO and founder (Building engineer)	Construction company	Bachelor's degree	11
3	Office manager (Architect)	Consultant office	Master's degree (Project management)	15
4	Architect	Consultant office	Bachelor's degree	3
5	Sustainability consultant	Consultant office	PhD degree (sustainable materials)	30
6	Project management (PMO)	Consultant office	PhD degree (energy efficiency in housing buildings)	12

7	Sustainability consultant Civil engineer Academic	Consultant office - Education sector	Master’s degree (energy and environment)	14
8	Project manager (Architect)	Consultant office	Bachelor’s degree	30
9	Office manager (Architect) Former CEO	Consultant office Semi-government organisation	Master’s degree	33
10	Urban designing	Consultant office	PhD degree	6
11	Civil engineer	Consultant office	Bachelor’s degree	4
12	Civil engineer	Consultant office	Bachelor’s degree	3
13	Engineering division head (Civil engineer)	Consultant office	Bachelor’s degree	29
14	Academic	Education sector	PhD degree (Sustainable materials)	13
15	Academic Architect	-Education sector Construction company Consultant office	PhD degree (sustainable housing buildings)	14
16	Academic	Education sector	PhD degree (Life Cycle Assessment)	15
17	Academic	Education sector	Master’s degree (sustainable planning and environmental policy)	7
18	Planner	Government sector (municipality)	PhD degree	10
19	Quality engineer	Government sector (municipality)	Bachelor’s degree	8
20	Quality engineer	Government sector (municipality)	Bachelor’s degree	8
21	Loss prevention engineer	Private company	Master’s degree (sustainable development)	11
22	Building engineer	Semi-government organisation	Master’s degree (engineering management)	8

4.7. Framework (RESAF) validation: Part 2—outline comparison

To validate RESAF, the case study outcomes were compared with the outcomes of existing studies regarding the sustainability of construction materials and the building in use (see Section 5.4). The comparison addressed the following key points:

- The RESAF outline and scope was compared to frameworks in past studies;
- Materials and their embodied effects had only been previously explored in one study by Asif et al. (2017);
- Energy consumption during the building's operation. A simplification was used for the RESAF house case study (kWh/m^2/year); this was compared with other houses' consumption as presented in past studies;
- While previous studies have not considered resilience at the building level, the resilience filter can be compared with that of other studies in terms of how buildings will meet sustainability requirements in the future;
- Guidance on the available regulations (Saudi Arabian building codes).

In short, the purpose of this process is to ensure the reliability of outcomes. For example, when RESAF provides results (i.e., kWh/m^2) for typical houses that are in line with those of existing studies, this is a positive sign (meaning that the calculations used are accurate; see Section 5.4.3). Ensuring that RESAF addresses the shortcomings of previous studies is another positive sign; see Section 5.4.1. All this would mean that RESAF performs well compared with previous studies.

4.8. Summary

This chapter has detailed the design of RESAF. The framework's two main elements are the simplified LCA approach used within the primary Environmental sustainability filter and the Urban Futures assessment used within the secondary Resilience filter. The Environmental sustainability filter involves three stages.

- Stage 1: Proposed construction material selection (cradle-to-gate)
- Stage 2: Transport selection (gate-to-grave)
- Stage 3: U-value calculation for domestic buildings

In addition, the chapter described the case study information and how to prepare it for RESAF. Regarding validation, Part 1 used interviews to explore participants' understanding of RESAF, and Part 2 assessed the framework's alignment with existing studies.

The next chapter presents and discusses the application of RESAF, with particular reference to the case study. As well the outcome of the validation process, Chapter 5 discusses the interview and comparison with past studies and how these influenced the final version of RESAF and the user manual.

5. Results and discussion

5.1. Introduction

This chapter presents the findings and discussion of the research, which are covered in four sections.

Section 5.2 describes the case study outcome when the RESAF beta version was applied. The outcome illustrates embodied carbon and energy figures, which are presented for both materials adopted, and subsequent in-use energy effects. Ways in which to achieve savings in these figures (through better material choices) is described. The future resilience of these material selections is also matter of concern, which is presented by use of a resilience assessment.

Sections 5.3 and 5.4 are the validation outcome with respect to the RESAF. There are two parts to the validation: analysing the feedback of potential stakeholders about the developed framework (see Section 5.3) and how the framework compared among existing studies, in addition to how the scope of this framework fills the gaps in knowledge for the existing literature base (see Section 5.4).

Section 5.5 discusses the influence of validation on the final RESAF version. Additionally, it discusses how the RESAF contributes to selecting the most appropriate materials that meet both the environmental sustainability and resilience requirements.

5.2. Case study findings

In agreement with the outline of the case study in Section 4.5.1, the proposed case study (for house design information, see Table 4-6 to 4-7 and Figure 4-9 to 4-12) is applied to the framework. The application of the case study will generate the main results. These outcomes are presented and analysed in the following Sections:

- Cradle-to-Gate (Section 5.2.1);
- Gate-to-Grave (Section 5.2.2);
- In-use consumption of energy (Section 5.2.3);
- The construction material stage and the in-use building stage – proposed alternatives (Section 5.2.4); and
- Future resilience of material choices (Section 5.2.5).

5.2.1. Cradle-to-Gate

The results from cradle-to-gate presented in Table 5-1 and Table 5-2 illustrate the embodied $kgCO_2e$ and MJ from the construction materials proposed by the case study designer. Overall, the influence of concrete materials on the outcome is clear for both embodied carbon and energy. This was to be expected, as, although the resources needed to produce concrete are available locally (Kisku et al., 2017), particularly in developing countries, the issue is that its manufacture involves a huge amount of energy, especially for the cement. In this building, it can be seen that steel has a considerable impact, with 11.51% of the total embodied carbon ($kgCO_2e$) and 16.46% of the total embodied energy (MJ). Steel and reinforced concrete are used extensively by structural engineers and architects, and both materials make intensive use of energy during their production (Yeo and Gabbai, 2011). Taken together, this indicates that the types of materials adopted need enhancing, or different materials need to be used to minimise the negative effects on the environment.

With these negative impacts in mind, a number of suggested actions will be highlighted for the case study. Looking ahead, specifying materials that have less impact on the environment, such as substitutes for cement (Monahan and Powell, 2011), could be a substantive step towards solutions for currently unsustainable materials.

The first action is to partially substitute cement with alternative materials when using ready-mix concrete, for example by using ground granulated blast furnace slag (GGBS) or pulverised fly ash (PFA). In Saudi Arabia, based on Ahmad et al. (2014), these cement replacements are abundantly available. Table 5-3 demonstrates the extent of the savings that can be made in terms of embodied carbon and energy (i.e. 76,084 kg of ready-mix concrete [25-30 MPa] and 1,870,152 kg for ready-mix concrete [28-35 MPa]). The savings could lead to a 41% reduction in embodied carbon and 27% reduction in energy consumption when substituting cement in this way. A further advantage of utilizing PFA or GGBS is that these “waste” materials would not need to be disposed of in a landfill, thus reducing the significant negative environmental impacts from a domestic building’s construction (Balaguera et al., 2018).

Table 5-1 Embodied carbon $kgCO_2e$ for cradle-to-gate

Material	Embodied carbon ($kgCO_2e$)[1]	%
Ready-mix concrete	287,434	46.94
Block (concrete products)	86,716	14.16
Steel	70,517	11.51
Cement (mortar)	54,642	8.92
Aluminium	44,270	7.23
Timber	38,087	6.22
Aggregate and sand	8,155	1.33
Plastics	7,810	1.28
Ceramics	6,629	1.08
Glass	3,578	0.58
Insulation	1,749	0.29
Carpet	1,484	0.24
Paint	983	0.16
Precast concrete	352	0.06
Total	612,406	100.00

[1]RESAF calculated embodied carbon ($kgCO_2e$) for the construction materials based on Equation (1a) in Section 4.2.1

Table 5-2 Embodied energy (MJ) for cradle-to-gate

Material	Embodied energy (MJ)[1]	%
Ready-mix concrete	1,845,880	31.84
Steel	954,248	16.46
Block (concrete products)	841,504	14.52
Aluminium	749,115	12.92
Timber	521,155	8.99
Cement (mortar)	328,839	5.67
Plastics	163,213	2.82
Aggregate and sand	128,596	2.22
Ceramics	101,988	1.76
Glass	62,275	1.07
Insulation	47,093	0.81
Carpet	26,830	0.46
Paint	23,646	0.41
Precast concrete	2,832	0.05
Total	5,797,214	100.00

[1]RESAF calculated embodied energy (MJ) for the construction materials based on Equation (1b) in Section 4.2.1

Table 5-3 The influence of blast furnace slag or fly ash replacement on embodied carbon $kgCO_2e$ and embodied energy (MJ) of ready-mix concrete ([25-30 MPa] and [28-35 MPa])

Material	Type[1]	Embodied carbon $kgCO_2e$	Total saving (%)	Embodied energy (MJ)	Total saving (%)[2]
Ready-Mix Concrete	100% Portland cement (CEM I)	287,434	0	1,845,880	0
Ready-Mix Concrete	Replacing cement with 15% fly ash	267,972	7	1,747,808	5
Ready-Mix Concrete	Replacing cement with 30% fly ash	240,648	16	1,592,109	14
Ready-Mix Concrete	Replacing cement with 25% blast furnace slag	230,993	20	1,611,571	13
Ready-Mix Concrete	Replacing cement with 50% blast furnace slag	170,736	41	1,339,859	27

[1] The compressive strength of ready-mix concrete does not change when the cement is partially substituted with PFA or GGBS.

[2] The relationship between the ready-mix concrete design (cement, water, sand, coarse aggregate, etc.) and embodied carbon is complex (for more information, see De Wolf, (2017)); this explains, for example, the more than double carbon saving with double fly ash replacement.

There are three types of blocks in the building: autoclaved aerated blocks, concrete blocks (8 MPa) and concrete blocks (12 MPa). They have been used as presented in detail in Table 5-4. Concrete blocks (12 MPa) and (8 MPa) will still be proposed. However, the second action is to change the selection of autoclaved aerated blocks to concrete blocks (8 MPa). This will result in a significant reduction (>20%) of embodied carbon and energy; Table 5-4 shows the breakdown of these savings in detail. The reason for this reduction is that autoclaved aerated blocks embody 3.50 MJ/kg and 0.326 $kgCO_2e$/kg, compared with 0.59 MJ/kg and 0.063 $kgCO_2e$/kg, respectively, for concrete blocks (8 MPa).

Table 5-4 Comparison of the two proposed options for blocks (concrete products) ready-mix concrete

	Old proposed option	New proposed option
Blocks (concrete products)	Autoclaved aerated block: 7,335 pieces, Concrete block (12 MPa): 2,819 pieces and Concrete block (8 MPa): 27,226 pieces	Concrete block (12 MPa): 2,819 pieces and Concrete block (8 MPa): 34,561 pieces
Embodied $kgCO_2e$	86,716 $kgCO_2e$	67,730 $kgCO_2e$ (22% saving)
Embodied energy (MJ)	841,504 MJ	624,314 MJ (26% saving)

5.2.2. Gate-to-Grave

The Transport (gate-to-grave) assessment examines how construction materials are delivered to the site and how they are disposed of at the end of the building's operation. Table 5-5 presents the transport information for materials based on the transport phase selection, which includes route, mode of transport, type and distance. Based on the available information, each construction material can have up to three transport phases. See Table 5-5, footnotes 2–5 for details about the transport phases. For example, for the concrete ready-mix, when it comes to transport phase (1), the route is delivery of concrete from the concrete plant to the construction site, the transport mode selected is HGV Diesel, the type selected is Rigid (>7.5–17 tonnes) and the distance is 14 km. In transport phase (2), the route is delivery of disposal concrete from the house location to the disposed site (after the house is demolished at the end life of the house), the transport mode is HGV Diesel, the type selected is Rigid (>17 tonnes) and the distance is 50 km. It has been presumed that most of the selected materials will be delivered locally from manufacturers in Saudi Arabia, except ceramic, granite and marble (from Italy, for example). It is also assumed that all the materials will be disposed of, except steel. Figure 5-1 represents the result: the transport from just gate-to-grave consumes approximately 75,118 $kgCO_2e$, while 612,406 $kgCO_2e$ is the consumption from cradle-to-gate for all activities (e.g. material processing and manufacturing, transport to the factory). Ignoring the transport from gate-to-grave is not a reasonable approach when calculating the embodied carbon, as it equals 12% of cradle-to-gate embodied carbon, as shown in Figure 5-1. Return of transport to its base has not been included because this is not directly controlled by the framework users who select the materials and potential suppliers; otherwise, the carbon emissions might increase twofold and reach 150,236 $kgCO_2e$.

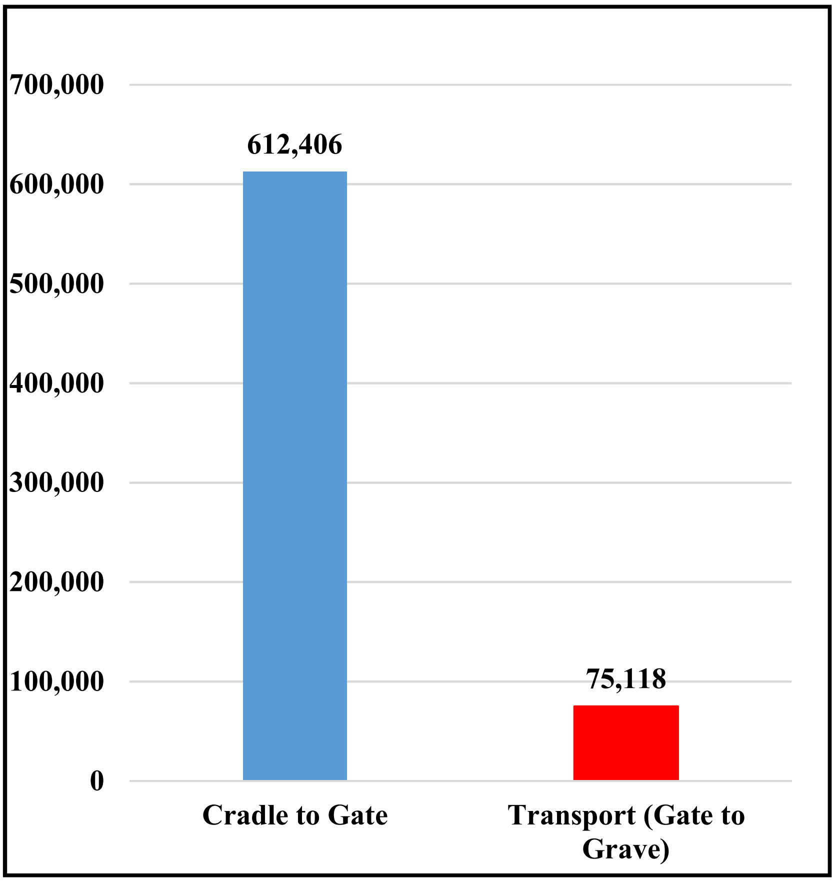


Figure 5-1 Comparison of cradle-to-gate and transport (gate-to-grave) in terms of embodied carbon $kgCO_2e$ for all materials (shown on vertical axis)

Table 5-5 Materials transport information

Materials inventory			Phase (1)			Phase (2)			Phase (3)			Embodied carbon ($kgCO_2e$)[1]		
NO.	Material	Type	Transport mode	Type	Distance	Transport mode	Type	Distance	Transport mode	Type	Distance	Freighting goods (downstream)	Well-to-tank (WTT) (upstream)	Freighting goods (upstream and downstream)
1	Ready-mix concrete	(25-30 MPa) - 100% Portland cement (CEM I)	HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	14	HGV Diesel	Rigid (>17 tonnes)	50				1,063	253	1,317
2	Ready-mix concrete	(28-35 MPa) - 100% Portland cement (CEM I)	HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	14	HGV Diesel	Rigid (>17 tonnes)	50				26,139	6,221	32,360
3	Cement	Mortar (1:3 cement: sand mix)	HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	139	HGV Diesel	Rigid (>17 tonnes)	50				14,523	3,455	17,978
4	Timber	Plywood	HGV Diesel	Rigid (>17 tonnes)	14	HGV Diesel	Rigid (>17 tonnes)	50				378	90	468
5	Precast concrete	(25-30 MPa) - 100% Portland cement (CEM I)	HGV Diesel	Rigid (>17 tonnes)	18.6	HGV Diesel	Rigid (>17 tonnes)	50				26	6	32
6	Block	Autoclaved aerated block	HGV Diesel	Rigid (>17 tonnes)	18.6	HGV Diesel	Rigid (>17 tonnes)	50				1,082	258	1,340

7	Block	Concrete block: (12 MPa)	HGV Diesel	Rigid (>17 tonnes)	18.6	HGV Diesel	Rigid (>17 tonnes)	50				1,179	281	1,459
8	Block	Concrete block: (8 MPa)	HGV Diesel	Rigid (>17 tonnes)	18.6	HGV Diesel	Rigid (>17 tonnes)	50				9,680	2,305	11,985
9	Insulation	Expanded polystyrene	HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	26	HGV Diesel	Rigid (>17 tonnes)	50				10	2	12
10	Soil	General aggregate	HGV Diesel	Rigid (>17 tonnes)	102	HGV Diesel	Rigid (>17 tonnes)	50				1,014	241	1,255
11	Timber	Laminated veneer lumber	HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	14	HGV Diesel	Rigid (>17 tonnes)	50				39	9	49
12	Glass	Toughened glass	HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	41	HGV Diesel	Rigid (>17 tonnes)	50				63	15	78
13	Aluminium	General aluminium	HGV Diesel	Rigid (>3.5 - 7.5 tonnes)	14	HGV Diesel	Rigid (>17 tonnes)	50				76	18	94
14	Plastics	PVC pipe	HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	14	HGV Diesel	Rigid (>17 tonnes)	50				34	8	42
15	Steel	Reinforcement steel	HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	41	HGV Diesel	Rigid (>17 tonnes)	50				896	213	1,110

16	Paint	General paint	HGV Diesel	Rigid (>17 tonnes)	370	Vans Petrol	Average - Petrol (up to 3.5 tonnes)	7	HGV Diesel	Rigid (>17 tonnes)	50	27	7	34
17	Carpet	Wool	HGV Diesel	Rigid (>17 tonnes)	370	Vans Petrol	Average - Petrol (up to 3.5 tonnes)	10	HGV Diesel	Rigid (>17 tonnes)	50	21	5	26
18	Ceramic	General ceramic	Cargo ship	Container ship	8190	HGV Diesel	Rigid (>17 tonnes)	80	HGV Diesel	Rigid (>3.5 - 7.5 tonnes)	20	1,328	266	1,594
19	Stone	Granite	Cargo ship	Container ship	8190	HGV Diesel	Rigid (>17 tonnes)	80	HGV Diesel	Rigid (>3.5 - 7.5 tonnes)	20	1,152	231	1,383
20	Stone	Marble tiles	Cargo ship	Container ship	8190	HGV Diesel	Rigid (>17 tonnes)	80	HGV Diesel	Rigid (>3.5 - 7.5 tonnes)	20	2,084	417	2,501
Total												**60,816 (81 %)**	**14,302 (19%)**	**75,118**

[1] RESAF calculated the total embodied carbon from transport construction materials based on Equation (2) in Section 4.2.2.
[2] For materials No. 1–14, phase 1 considers the delivery of materials from the factory to the construction site. In contrast, phase 2 considers the delivery of disposal materials from the house location to the disposed site (after the house is demolished at the end life of the house).
[3] For material No. 15, phase 1 considers the delivery of materials from the factory to the construction site. Phase 2 considers the delivery of disposal materials to the recycling facility.
[4] For materials No. 16 and 17, phase 1 considers the delivery of materials from the factory to the warehouse. Phase 2 considers the delivery of materials from the warehouse to the construction site. Phase 3 considers the delivery of disposal materials from the house location to the disposal site.
[5] For materials No. 18–20, Phase 1 considers the delivery of materials from the port in Italy to the port in Saudi Arabia. Phase 2 considers three things: delivery of materials from the factory to the port in Italy + delivery of materials from the port in Saudi Arabia to the warehouse + delivery of disposal materials from the house location to the disposal site. Phase 3 considers the delivery of materials from the warehouse to the construction site.

In Figure 5-2, ready-mix concrete, cement and concrete blocks are the main contributors to embodied carbon from freighting goods and WTT, even though they are locally sourced. Aggregate and sand (including marble and granite, sourced from Italy, and gravel, which is locally sourced) still reach 5,140 kgCO_2e. Other materials (insulation, carpet, precast concrete, paint, plastic, glass and aluminium) have no tangible effect on the embodied carbon. Freighted goods' carbon emissions are dramatically higher, with 81% of the total embodied carbon transport from gate-to-grave, compared with WTT emissions (see Table 5-5). No direct solution can be proposed, and whenever possible, materials are sourced locally, which reduces carbon emissions. A number of studies have highlighted the necessity of reducing carbon dioxide emissions which arise from the transportation of materials both during the distribution of materials and the construction stage (Ng et al., 2012). It is, therefore, suggested that companies should make an effort to select the nearest supplier and avoid deliveries of small amounts of goods. Bear in mind that the impact of transportation can still be high if low-energy materials are transported over long distances (Vukotic et al., 2010).

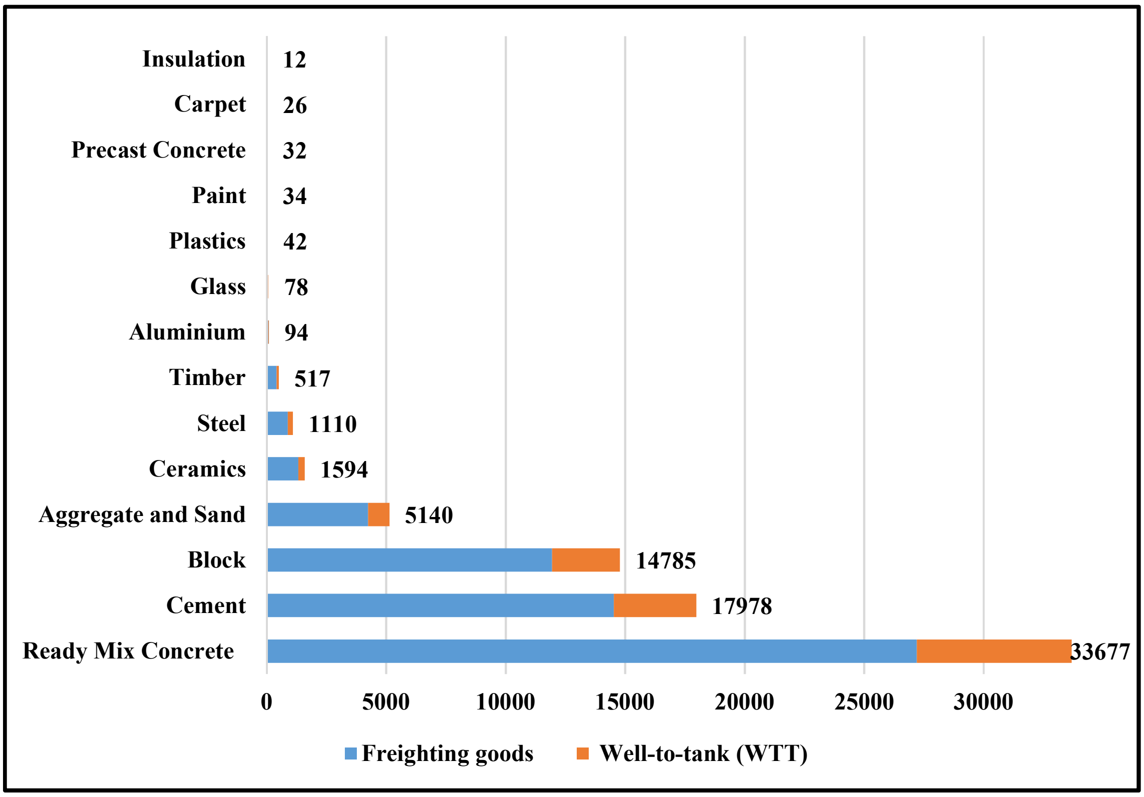


Figure 5-2 Both freighting goods and WTT embodied carbon for transport (gate-to-grave) – horizontal scale shows embodied kgCO_2e

5.2.3. In-use consumption of energy

It is not sufficient to calculate the improvement to embodied energy alone due to material choices made. A holistic assessment should also look at the impact that these choices have on the yearly energy demand (consumption) for the heating or cooling load in the domestic property during the operation of the building. With the material properties proposed, the respective U-value properties for each of the building elements adopted are presented in Table 5-6. Contribution to heat gain or loss coefficient from ventilation ($H_{t\ (ventilation)}$) is calculated as 431.39 ($W\ K^{-1}$), the building volume is 3,735 m^3, and the rate of air changes per hour is 0.35 ACH (Çengel and Ghajar, 2015) [RESAF calculated the contribution to heat gain or loss coefficient from ventilation based on Equation (7) in Section 4.2.3.4].

Based on these values, a building in Dammam City (zone 1) would be expected to consume on average a total of 176,295 kWh of energy per year (198 $kWh/m^2/year$) [RESAF calculated yearly energy consumption based on Equations (5a) and (5b) in Section 4.2.3.4; see Figure 5-3]. Breaking this number down into detail, 94% (166,080 kWh/year) is for cooling and 6% (10,215 kWh/year) is for heating. Assuming that 0.726 $kgCO_2e/kWh$ is the factor for conversion from energy used to carbon emitted in Saudi Arabia [this has been adapted by adding 6% to the 0.685 $kgCO_2/kWh$ factor provided by Taleb and Sharples (2011) based on a recommendation by Hammond and Jones (2011a)], it can be calculated that during its operation stage, the Base Case building in Dammam embodies 127,990 $kgCO_2e$ / yr.

Table 5-6. Properties of elements used in the case study building – Base Case

Building elements[1]	Details	U-value (W/m^2K)[2]	Area (m^2)	Contribution to heat gain or loss coefficient (H_t) ($W\ K^{-1}$)[3]
Roof 1	Ceramic (20 mm), polyurethane (0.20 mm), polystyrene 'extruded' (20 mm), bitumen (4 mm), cement mortar '1650 kg/m³' (10 mm), reinforced concrete (200 mm)	0.946	175	165.57
Roof 2	Gravel (30 mm), polyurethane (0.20 mm), polystyrene 'extruded' (20 mm), bitumen (4 mm), cement mortar '1650 kg/m³' (10 mm), reinforced concrete (200 mm)	0.909	175	159.04
Wall 1	Granite (20 mm), masonry block (200 mm), polystyrene 'extruded' (20 mm), cement mortar '1650 kg/m³' (10 mm)	0.868	580	503.22
Wall 2	Masonry block, (200 mm), polystyrene 'extruded' (20 mm), cement mortar '1650 kg/m³' (20 mm)	0.862	290	249.84
Window	Double glazing, aluminium frame, air filled, low emissivity: εn = 0.1 'soft coat', 12-mm gap between panes and 8-mm thermal break	2.50	133.20	333
Ground floor	Land soil type is sand or gravel, and polystyrene 'extruded' (20 mm) is used for the insulation.	0.41	381	156.21

[1] Design assumptions: the base case of the domestic building is designed to have two types of walls and roofs. The Wall 1 type of 580 m^2 is used in the main elevation and in most parts of the building's side elevations. The Wall 2 type of 290 m^2 is used in the back elevation and in the rest of the side elevations. In regard to Roof 1 and 2 (both types covering 175 m^2), the first type with gravel is used near the machines in the roof, while the second type with ceramics is used on the other spaces in the roof.
[2] RESAF calculated the U-values for the walls and roof based on Equation (3) and (4) in Section 4.2.3.1, the window based on the criteria table (see Section 4.2.3.2) and the ground floor based on the criteria table (see Section 4.2.3.3).
[3] RESAF calculated the contribution to heat gain or loss coefficient (H_t) for building elements based on Equation (6) in Section 4.2.3.4.

- Contribution to the heat gain or loss coefficient H_t of a Base Case house (Dammam city): $H_{t\ (Roof\ 1)}$ = 165.57 W K^{-1}, $H_{t\ (Roof\ 2)}$ = 159.04 W K^{-1}, $H_{t\ (Wall\ 1)}$ = 503.22 W K^{-1}, $H_{t\ (Wall\ 2)}$ = 249.84 W K^{-1}, $H_{t\ (window)}$ = 333 W K^{-1}, $H_{t\ (ground\ floor)}$ = 156.21 W K^{-1} and $H_{t\ (ventilation)}$ = 431.39 W K^{-1}.

Therefore the total $H_t = H_{t\ (Roof\ 1)} + H_{t\ (Roof\ 2)} + H_{t\ (Wall\ 1)} + H_{t\ (Wall\ 2)} + H_{t\ (window)} + H_{t\ (ground\ floor)} + H_{t\ (ventilation)}$ = 1998.27 W K^{-1}

- Cooling degree-days (CDD) and Heating degree-days (HDD) for Dammam city = 3463 and 213 °C, respectively. (See Table 7– Appendix E)

Annual cooling energy demands (Q_c) =

H_t x CDD x 24 / 1000 =

1998.27 x 3463 x 24 / 1000 =

166,080 kWh / year

Equation 5a

Annual heating energy demands (Q_h) =

H_t x HDD x 24 / 1000 =

1998.27 x 213 x 24 / 1000 =

10,215 kWh / year

Equation 5b

Annual energy consumption = (Q_c) + (Q_h) =

166,080 + 10,215 = **176,295 kWh / year**

Annual energy consumption per m^2 =

Annual energy consumption / Total floor area of the building =

176,295 / 890 = **198 kWh / m^2 / year**

Figure 5-3 How RESAF calculates the yearly energy consumption (kWh/year) and (kWh/m^2/year) for the Base Case (Dammam city)

A study by Alaidroos and Krarti (2015b) reported the energy consumption in different cities for domestic buildings with the same properties, but the study did not include embodied carbon. Because the developed framework provides an option to select other cities, Figure 5-4 and Figure 5-5 illustrate the energy consumption and embodied $kgCO_2e$ in different cities. These cities are Riyadh, Median, Makkah, Jeddah, Gassim and Dammam for zone 1, Tabuk and Khamis Mushait for zone 2 and Abha for zone 3 (see Figure 2-3 in Section 2.2). The figure of 198 $kWh/m^2/yr$ is dramatically high in comparison with other benchmarks [See Table 2-10 in Section 2.3.2.1] and is no where near achieving the performance of a passive design (typically 15 $kWh/m^2/yr$). In other words Carbon neutrality may be some way off yet for Saudi Arabia; however, it has been proposed that the domestic sector in Saudi Arabia should aim to achieve low-carbon energy consumption rates of approximately (77 to 98) $kWh/m^2/yr$ (Aldossary et al., 2017). It is therefore interesting to note that the yearly embodied figures for two cities, Khamis Mushait (zone 2) and Abha (zone 3), are 73 $kWh/m^2/yr$ (53 $kgCO_2e/m^2/yr$) and 70 $kWh/m^2/yr$ (51 $kgCO_2e/m^2/yr$), respectively, which actually meet the low-carbon embodied benchmark recommended by Aldossary et al. (2017), whereas that for another city, Makkah (zone 1), is 260 $kWh/m^2/yr$ (189 $kgCO_2e/m^2/yr$), which is the highest.

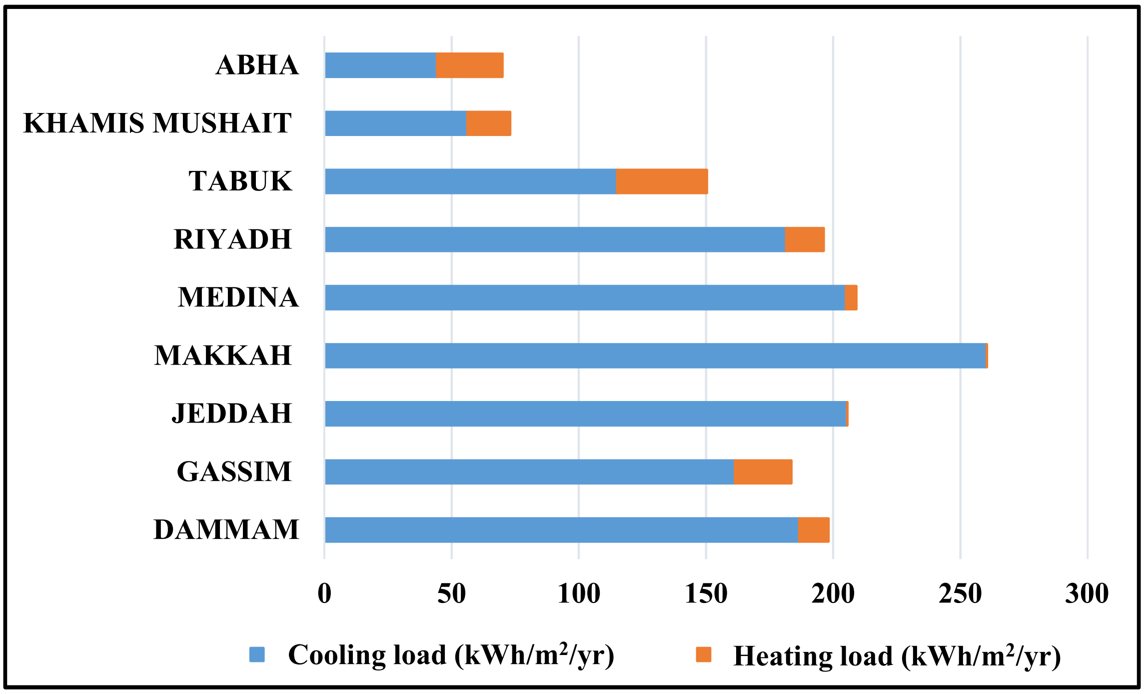


Figure 5-4 A comparison of the heating and cooling performance (Energy requirements - kWh/m^2 /yr) of Base Case within different cities of Saudi Arabia

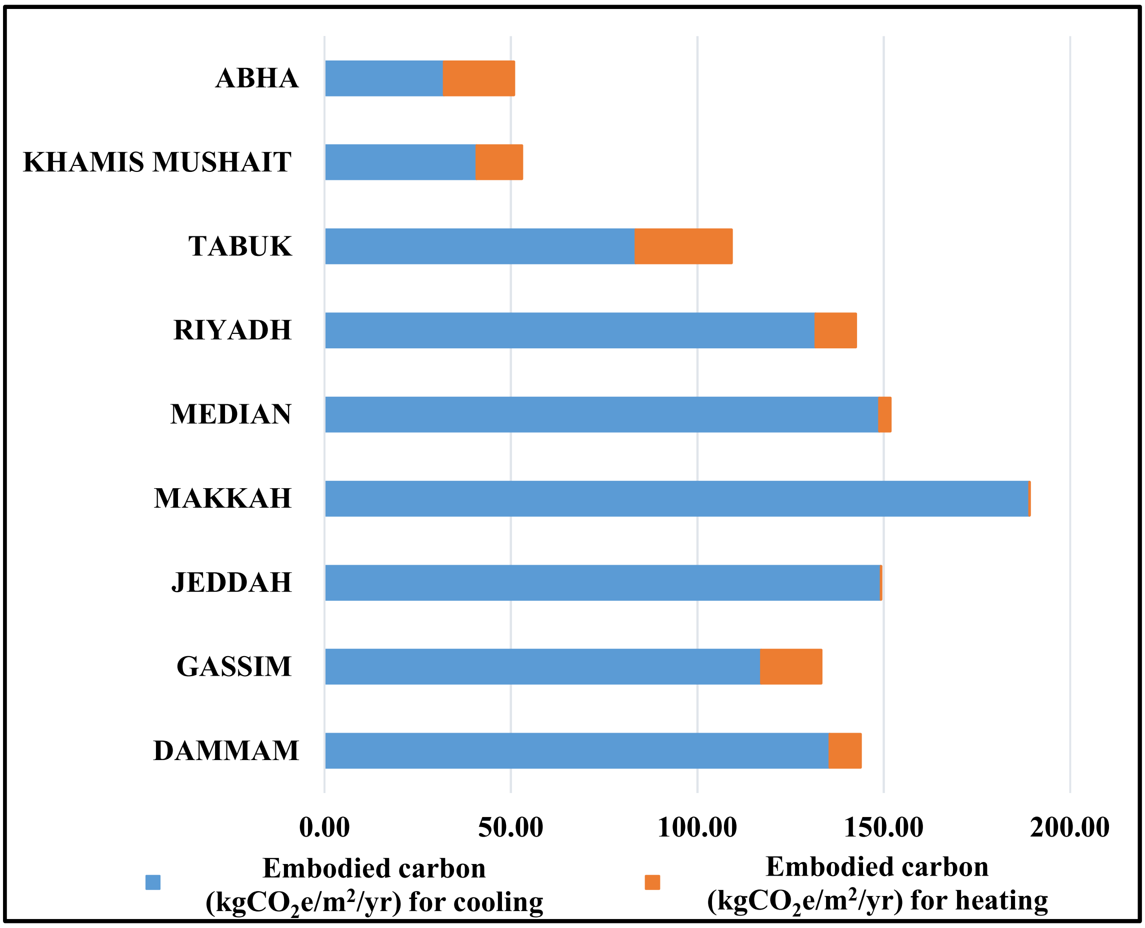


Figure 5-5 A comparison of the heating and cooling performance (Related Embodied carbon - $kgCO_2e/m^2/yr$) of Base Case within different cities of Saudi Arabia

The figures for all the cities (in all three zones) are most significantly influenced by cooling load, with only a slight effect from the heating load. A reduction in the $kWh/m^2/yr$ or $kgCO_2e/m^2/yr$ rates, as presented in Figure 5-4 and Figure 5-5 respectively can be achieved by using additional or replacement insulation for walls and roofs and by changing the type of windows adopted. This is especially true because these materials do not have tangibly negative impacts on the environment in terms of overall embodied carbon and energy (refer to Table 5-1 and Table 5-2 for more information). Table 5-7 shows the annual energy and carbon savings of the six options according to the different changes to elements. In Table 5-7, for example, in Option 2, by increasing the extruded polystyrene from 20 mm to 30 mm for the walls and roofs, changing the window type to triple glazing and retaining the other originally proposed elements (in Table 5-6), annual energy consumption and carbon emissions can be reduced by approximately 17%. This reduction can also further reduce to 19% if the window frames are replaced with plastic (PVC), as in Option 3.

Table 5-7 Proposed changes to specific properties of elements and respective savings in energy (and related embodied Carbon) for heating and cooling

And Options	Proposed changes to elements[1]		% Saving for energy consumption compared to Base Case (Figure 5-4)
	Walls and roofs	Windows	
1	Increase extruded polystyrene from 20 mm to 30 mm	No changes	13
2	Increase extruded polystyrene from 20 mm to 30 mm	Replace the double glazing with triple glazing and keep the aluminium frame	17
3	Increase extruded polystyrene from 20 mm to 30 mm	Replace the double glazing with triple glazing and change to PVC frame	19
4	Replace extruded polystyrene with polyisocyanurate board (30 mm for walls and 60 mm for roofs)	No changes	26
5	Replace extruded polystyrene with polyisocyanurate board (30 mm for walls and 60 mm for roofs)	Replace the double glazing with triple glazing and keep the aluminium frame	30
6	Replace extruded polystyrene with polyisocyanurate board (30 mm for walls and 60 mm for roofs)	Replace the double glazing with triple glazing and change to PVC frame	32

[1] Other properties have not been changed in Table 5-6

Savings could also further increase up to 32% if the insulation material type is changed to polyisocyanurate (see Options 4 to 6). The reason behind the extra savings is the thermal conductivity for polyisocyanurate, which is 0.02 W/m K, compared to 0.027 for extruded polystyrene, so lesser U-values can be achieved for walls and roofs (see Table 5-8 for buildings elements' U-values for different options; properties already reported in Table 5-7). Whether certain U-values (W/m^2K) comply with the Saudi Energy Conservation Code–Low-Rise (Residential) Buildings (SBC 602) (SBC, 2018a) and Green Building Code (SBC 1001) (SBC, 2018b) is dependent on the city location (zone). The assumption will be made based on fact that the U-values should not exceed 0.31 W/m^2K for roofs and 0.53 W/m^2K for walls, and this should be applied to all Saudi Arabian cities. Therefore, Options 1 to 3 are not enough to meet these codes, while Options 4 to 6 do meet these codes. This will be analysed further in section 5.2.4, when the alternatives for both (the construction materials and the in-use building) stages have been presented.

Table 5-8 U-value options for buildings elements

	U-values (W/m²K)				
Options	Roof 1	Roof 2	Wall 1	Wall 2	Window
Base case	0.95	0.91	0.87	0.862	2.50
1	0.70	0.68	0.66	0.653	2.50
2	0.70	0.68	0.66	0.653	1.90
3	0.70	0.68	0.66	0.653	1.60
4*	0.30	0.30	0.52	.52	2.50
5*	0.30	0.30	0.52	.52	1.90
6*	0.30	0.30	0.52	.52	1.60

*Meet Saudi Energy Conservation Code–Low-Rise (Residential) Buildings (SBC 602) and Green Building Code (SBC 1001)

The yearly energy consumption for cooling (kWh/m^2/yr) within the Base Case and all six options in all 9 Cities in Saudi Arabia are presented in Figure 5-6. The RESAF in the main case study Dammam reduced from 187 to 162, 155, 151, 138, 131, and 127 kWh/m^2/yr based on options 1 to 6, which reduced the cooling energy demands by 32% during operation. Again, houses placed in other cities around the country would gain reasonable savings in in-use cooling energy (around 13 to 32 %).

The yearly energy consumption for heating (kWh/m^2/yr) within the Base Case and all six Options in all 7 Cities in Saudi Arabia are presented in Figure 5-7. Notice that Jeddah and Makkah are not included here, as their original heating load was less than 1 kWh/m^2/yr which would have minimal impact. In these cities further reductions in-embodied energy can be achieved as the users do not need to adopt a heating system and need only a cooling system. If the same approach were implemented in the Base case study in Dammam city, around 9 kWh/m^2/yr (5% of total energy) could be saved, leading to savings of around 24% instead of 19% in Option 3 (this could be applied in all 6 options). However, this is only an example of an idea that a RESAF user might explore based on the design requirements and the city heating / cooling requirements.

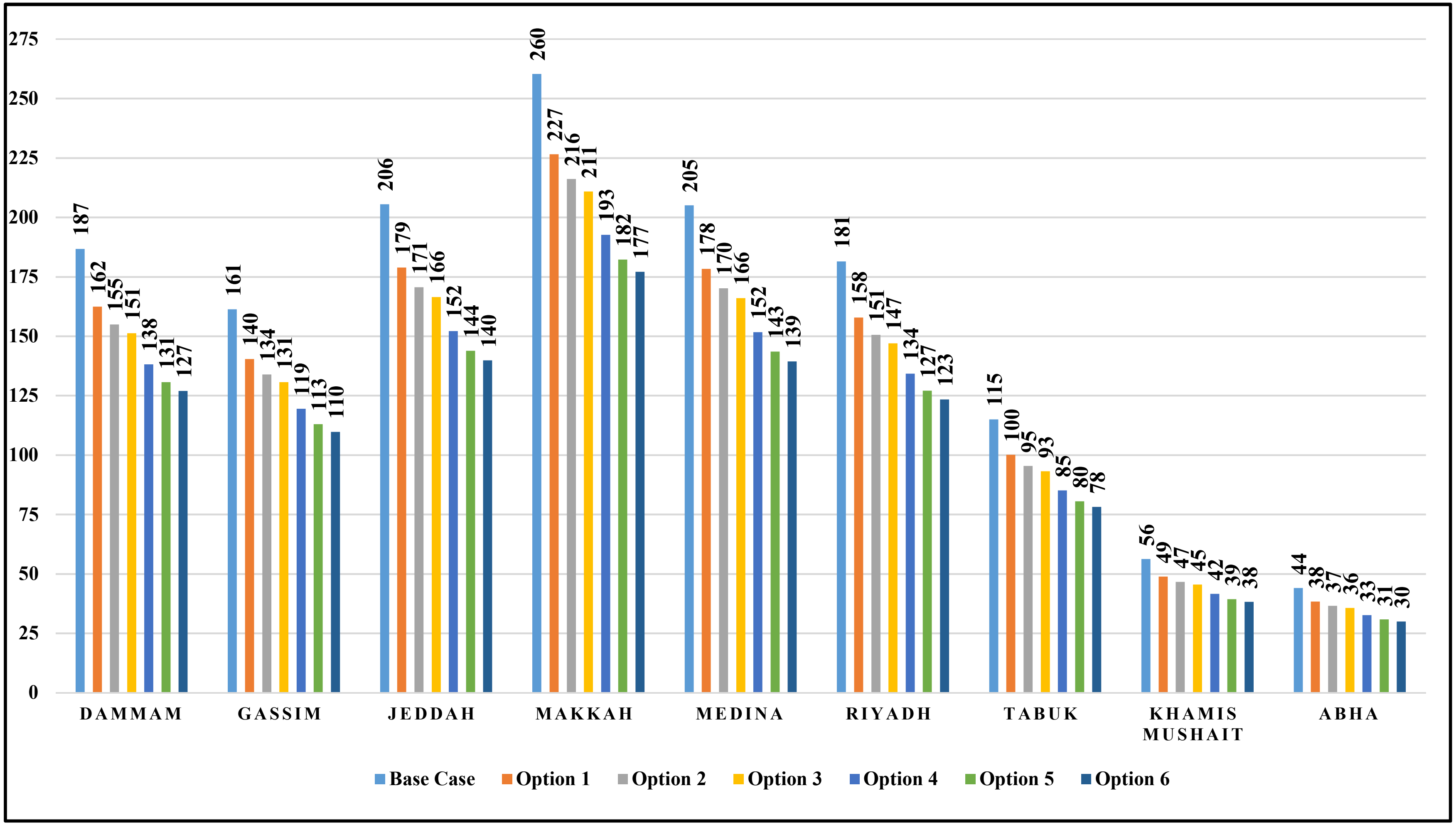


Figure 5-6 Different cities' cooling loads for proposed change options (kWh/m^2/yearly)

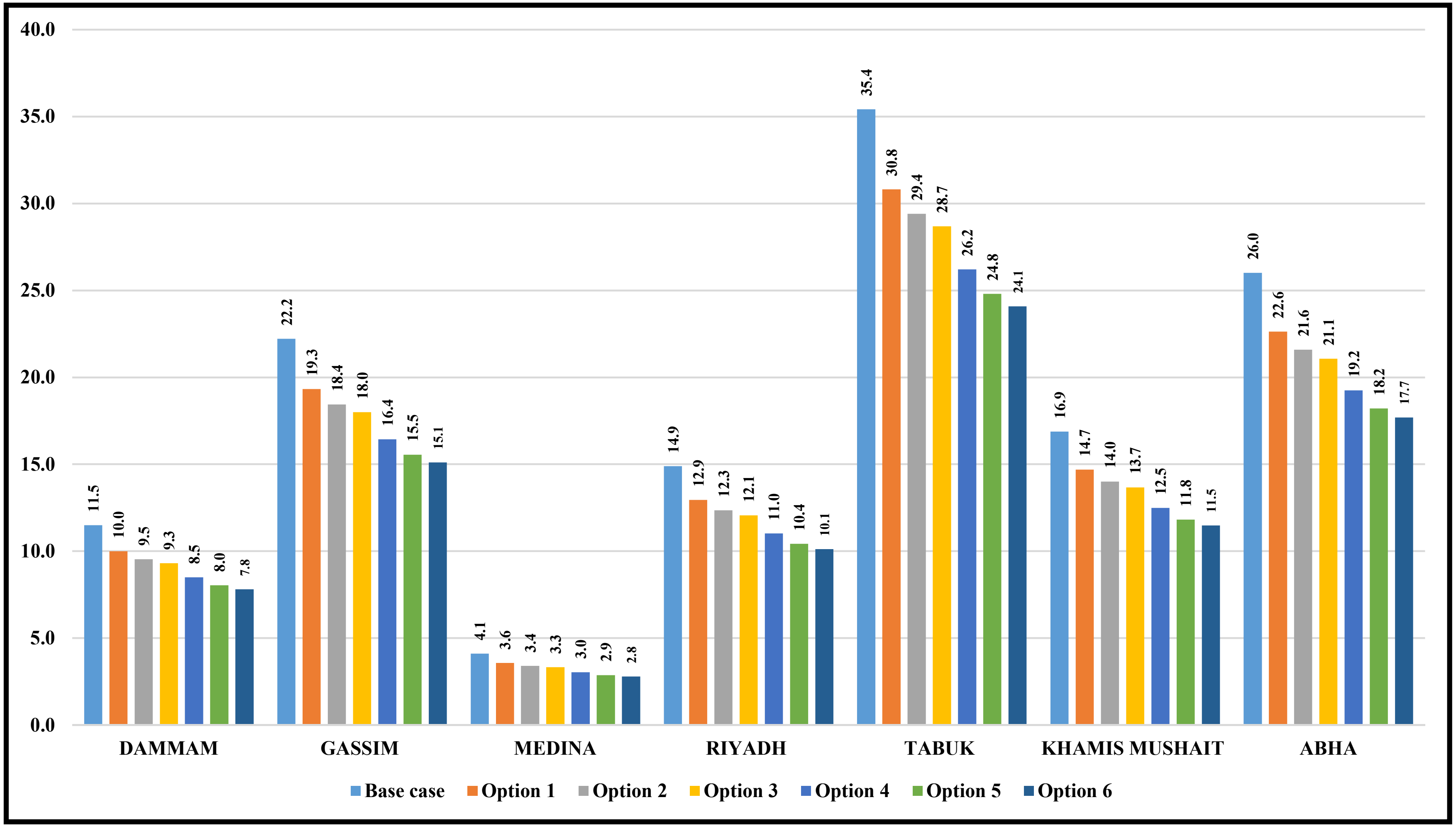


Figure 5-7 Different cities' heating loads for proposed change options (kWh/m^2/yearly)

5.2.4. The construction material stage and the in-use building stage

In this section, five alternatives are illustrated in Table 5-9 to outline the environmental impacts of both the construction material stage and the in-use building stage (for Dammam city). Table 5-9 reflects and combines the proposed changes, as follows:

1. The influence of cement replacement in Table 5-3;
2. Replacing the autoclaved aerated block in Table 5-4; and
3. Specific properties of elements for improving the in-use energy in Table 5-7.

It is worth noting that when in-use stage changes are not made (Alternative 1), there is no change to the long-term energy consumption during building operation. The only benefits of the cradle-to-gate materials stage are further reductions in the embodied carbon (22.16%) and energy (12.48%). Therefore, other alternatives (2 to 5) reported to gain savings for in-use energy are as follows.

5.2.4.1. Explanation of alternatives

Alternative 2 shows a 17% reduction in yearly energy consumption and carbon production: 145,792 kWh/yr and 105,845 $kgCO_2e/yr$ (164 $kWh/m^2/yr$ and 119 $kgCO_2e/m^2/yr$). In short, a slight increase of around 1% in embodied energy and carbon from materials compared to Alternative 1 (which comes from changes to choices of glass and insulation used) is well worth the trade-off when a considerable amount more can be saved every year of use. However, Alternative 3 demonstrates 19% savings in energy use, as well as slightly higher savings of around 1% in embodied carbon and energy from materials, compared to Alternative 1. The reason for this slight improvement is that the PVC used as a frame for the windows has much lower carbon and energy coefficients (in MJ/kg and $kgCO_2e/kg$) than aluminium (see Table 1–Appendix E).

Although alternatives 2 and 3 offer good savings in-use energy savings compared to the original design (base case), (17 and 19% respectively), however they have unfortunately not met the U-value requirements presented in Section 5.2.3. The reason these alternatives have been analysed even though they do not meet the codes is that applying the RESAF to a case study is a long process, and users are expected to discover many alternatives on their way to reaching their design needs. In addition, the base case is based on a real design (which was designed recently); consequently, any savings in energy consumption and carbon footprint (achievable from Alternatives 2 and 3) are better than the current situation. An extension to the decision-making process is to find the optimal choice that delivers an appropriate U-value, with minimal embodied carbon (from material choice and long-term in-use performance) achievable at the least cost. Whilst the later aspect is something not considered in this research it forms an area for future work.

On the principle of complying with codes (U-value requirements), Alternatives 4 and 5 are suited to meet the requirements with 30 and 32% savings, respectively. The effects will be similar to Alternatives 2 and 3 concerning the materials embodied in Alternative 4 (window aluminium frame) and Alternative 5 (window PVC frame). The insulation type or thickness does not have a tangible effect; it is approximately 1 to 2 % of the overall embodied carbon or energy for materials.

5.2.4.2. Summary of findings for LCA aspects

There are a number of notable findings in both the construction material stage and the in-use building stage.

Firstly, it has been shown that significant annual reductions in heating and cooling requirements will also apply to the other Saudi Arabian cities in the three zones (see Figures 5-6 and 5-7). This means that during the building life cycle, this will result in many years of savings from the viewpoints of both the materials and the enhanced in-use performance of the building. Over a 50- to 100-year lifespan, this saving could be considerable (i.e. up to 100 times or more).

Secondly, far too many Saudi studies have previously simply ignored embodied carbon and energy from materials (Alaidroos and Krarti, 2015b; Felimban et al., 2019). It seems they did so because the in-use stage comprises the majority of the energy consumption for a building. This philosophy might be considered at best over-simplified and at worst inaccurate, especially when one examines Table 5-9 and compares alternative cases versus to the base case. The embodied energy of the materials is equal to approximately nine years of energy consumption from building operation, and the carbon equals approximately five years of annual carbon emissions from building operation. This shows that ignoring it might not be appropriate, and it very much justifies the research presented here.

Thirdly, the base case design is an actual case design representative of many of the newer domestic properties being built in Saudi Arabia to current improved standards (see Section 4.5.1). As such it was originally designed with insulation polystyrene ‘extruded’ (20 mm only) and double glazing (see Table 5-6). As part of this research suggestions were made using RESAF to help reduce the embodied energy of the materials used and further improve the long-term performance. Other recent studies, including Abuhussain et al. (2018), Ahmed et al. (2019) and Alghamdi, 2019, when assessing Saudi Arabian houses, assumed that the base case would be without insulation and a single clear glazing, which may not reflect newly built modern houses in the country. In the case study applied, if it was assumed that the design has no insulation in place and clear single glazing, the house may consume around 443 kWh/m^2/yr (instead of 198 kWh/m^2/yr). Therefore the savings, when compared to these base cases, could be higher than those reported in Table 5-9.

Fourthly, RESAF users may need to address the concerns with respect to the larger size of a typical house (villa); users may re-design the house and reduce the size by 50% (see Section 4.5.1.1). If such an idea is applied, additional savings will be obtained in terms of the environmental impacts for both the construction material stage and the in-use building stage. In Table 5-9, for example, the yearly energy consumption (in-use stage) savings in alternative 5 will be 64% instead of 32%. Note that this idea was not part of the current study, as it requires examining the architectural principles of the house design (i.e. rooms’ areas and functions) to come up with the optimal house size.

Other points will be raised in Section 5.4 (Validation part 2 - Comparison results). The next section considers the resilience filter, which will determine the future resilience of these material choices (solutions) to reduce energy and carbon.

Table 5-9. Different alternatives for use of the framework

Aspects	Base Case	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Changes to minimise the embodied energy and carbon from materials	No changes	Use ready-mix concrete, replacing the cement with 50% blast furnace slag; replace autoclaved aerated blocks with concrete blocks (8 MPa)	Use ready-mix concrete, replacing the cement with 50% blast furnace slag; replace autoclaved aerated blocks with concrete blocks (8 MPa)	Use ready-mix concrete, replacing the cement with 50% blast furnace slag; replace autoclaved aerated blocks with concrete blocks (8 MPa)	Use ready-mix concrete, replacing the cement with 50% blast furnace slag; replace autoclaved aerated blocks with concrete blocks (8 MPa)	Use ready-mix concrete, replacing the cement with 50% blast furnace slag; replace autoclaved aerated blocks with concrete blocks (8 MPa)
Changes to minimise the in-use energy (1)	No changes	No changes	Walls and roofs: Increase extruded polystyrene from 20 mm to 30 mm	Walls and roofs: Increase extruded polystyrene from 20 mm to 30 mm	Replace extruded polystyrene to polyisocyanurate board 30 mm (walls) and 60 mm (roofs)	Replace extruded polystyrene to polyisocyanurate board 30 mm (walls) and 60 mm (roofs)
Changes to minimise the in-use energy (2)	No changes	No changes	Replace the double glazing with triple glazing and keep the aluminium frame	Replace the double glazing with triple glazing and replace with PVC frame	Replace the double glazing with triple glazing and keep the aluminium frame	Replace the double glazing with triple glazing and replace with PVC frame
Embodied energy from materials	5,797,214 MJ or 1,610,349 kWh	5,074,001 MJ or 1,409,456 kWh (12.48% savings)	5,123,081 MJ or 1,423,090 kWh (11.63% savings)	5,010,774 MJ or 1,391,893 kWh (13.57% savings)	5,139,765 MJ or 1,427,724 kWh (11.34% savings)	5,027,457 MJ 1,396,527 kWh (13.28 % savings)
Embodied carbon from materials	612,406 $kgCO_2e$	476,720 $kgCO_2e$ (22.16% savings)	479,175 $kgCO_2e$ (21.76 % savings)	471,811 $kgCO_2e$ (22.96 % savings)	480,135 $kgCO_2e$ (%21.60 savings)	472,772 $kgCO_2e$ (22.80 % savings)
Yearly energy consumption (in-use stage)	176,295 kWh (198 kWh/m^2)	176,295 kWh (198 kWh/m^2) (no savings)	145,792 kWh (164 kWh/m^2) (17% savings)	142,266 kWh (160 kWh/m^2) (19% savings)	123,510 kWh (139 kWh/m^2) (30% savings)	119,984 kWh (135 kWh/m^2) (32% savings)
Yearly embodied carbon (in-use stage)	127,990 $kgCO_2e$ (144 $kgCO_2e/m^2$)	127,990 $kgCO_2e$ (144 $kgCO_2e/m^2$) (no savings)	105,845 $kgCO_2e$ (119 $kgCO_2e/m^2$) (17% savings)	103,285 $kgCO_2e$ (116 $kgCO_2e/m^2$) (19% savings)	89,668 $kgCO_2e$ (101 $kgCO_2e/m^2$) (30% savings)	87,109 $kgCO_2e$ (98 $kgCO_2e/m^2$) (32% savings)

[1]Refer to Table 4-8 for base construction materials for the case study.

5.2.5. *Future resilience of material choices*

This domestic building case study utilises a number of proposed solutions, such as partially replacing cement for concrete mix, not using autoclaved aerated blocks, increasing insulation thickness and using triple-glazed windows with PVC frames. The proposal of solutions leads to a worthwhile question: are the solutions fit-for-purpose in the future? Table 5-10 and Table 5-11 offer an assessment of this by considering their resilience within three well-reported future scenario archetypes drawn from the literature: *The new sustainability paradigm, Policy reform and Market forces* (see Hunt et al., 2012, Lombardi et al., 2012) [For a brief descriptive narrative of these scenarios see Chapter 4, Section 4.3]. This Urban Futures methodological approach helps evaluate whether the proposed solutions can be implemented and whether they will function and cope with changes in the future. The following is a description of the necessary conditions (NCs 1 to 6) (Table 5-10 and Table 5-11).

5.2.5.1. *(NC 1): Availability of proposed materials*

In this case study, PFA and GGBS have been proposed as alternatives to using a percentage (up to 50%) of cement and as ways to reduce the carbon and energy footprint for concrete. The availability of materials is an important factor in the selection of materials in the construction industry. Availability is paramount because specific materials might be in irregular (or limited) in supply, and regulations to enforce their adoption (in a push to be more sustainable, for example) could lead to an increase in demand by stakeholders in the market.

Concrete producers should therefore be prepared to make these cement substitutes readily available. High demand for specific materials leads to a shortage, which will be reflected in the price. The search for replacements for cement will provide more alternatives for the industry. Based on a study by Kupwade-Patil et al., (2018), one example is pozzolans, which can be found in Saudi Arabia. This supports the proposal to reduce the environmental impacts of concrete production using a number of cement alternatives, not just PFA and GGBS. More than that, depleting of resources in the future should be taken into account. To avoid this, a balance is recommended. Again, the several alternatives proposed should provide a reasonable approach.

Table 5-10 Assessing the resilience of possible sustainable solutions in the future for the case study (NC 1-3)

Necessary conditions (NC)[1]	**New Sustainability Paradigm (NSP)**	**Policy Reform (PR)**	**Market Forces (MF)**
1- Availability of proposed materials	Availability is less-well considered initially, and partial replacement of cement with other substitutes (PFA or GGBS) ensues. With time, availability becomes a concern, as does the reliance on coal for PFA production.	Availability is less well considered. Domestic building policies require a minimum cement replacement in order to help meet carbon targets, which are a primary focus.	Concerned with developing a market to increase the demand for these materials for concrete factories; this is accompanied by an increased search for other substitutes (options such as pozzolans) to meet the policy standards.
2- Bounce-back ability of the building	Partial replacement of cement with other substitutes (PFA or GGBS) is readily endorsed as it avoids waste and reduces carbon – bounce-back is less well-considered.	Long-term resilience of the material itself is less well considered than ability to meet carbon targets – a strict structural design requirement for cement replacement is set.	The market is concerned with minimising costs by following exact design principles (i.e. original minimum compressive strength); longevity is considered only where costs and liability occur.
3- Absence of other environmental considerations	The importance of replacing high-impact materials such as aluminium frames with other types (e.g. PVC) is an initial priority. As durability concerns are raised, sustainable alternatives are proposed.	As durability concerns are raised about the resilience of materials to hot weather conditions, policy reacts. A dual approach is adopted: use of recycled PVC in frame production and adoption of PVC frames with triple glazing adopted in cities with lower temperatures, and retaining aluminium frames with triple glazing for hot regions.	The market is interested in meeting the conditions for reasonable low cooling and heating energy to avoid other environmental concerns.

[1] The commentaries for each of the scenarios were based on available information in the literature review and on Saudi Arabian construction industry practice.

Table 5-11 Assessing the resilience of possible sustainable solutions in the future for the case study (NC 4-6)

Necessary conditions (NC)	New Sustainability Paradigm (NSP)	Policy Reform (PR)	Market Forces (MF)
4- Environmental footprint of transport	NSP considers whole-life costing in order to ensure the environmental footprint of transport is considered as a whole.	Where the material comes from is less important than meeting targets and ticking checklist items; while promotion for transportation (with low carbon emissions) is regulated and enforced, the bigger picture is sometimes missed.	Any attempt to minimise the transportation of goods (construction materials) is considered purely on an economics basis – if it saves money, it is readily adopted. Only where a long-term interest for the building is served will a higher price be paid to reduce the footprint.
5- Minimum building code requirements	A target of maximum U-values, annual energy consumption and other building material specifications are readily and willingly exceeded.	Building regulations set ever tighter U-values for building elements (e.g. yearly energy consumption); this includes a maximum embodied carbon threshold for materials use.	MF implements these rules gradually rather than immediately stimulating new markets. The bare minimum is achieved, and exceedance occurs only where a market advantage is served.
6- Public acceptance of sustainable solutions	Public ability to accept these changes (people's behaviour) is high, especially when it comes to understanding sustainability concerns.	Acceptance is enforced by policy rather than being readily accepted. Acceptance is promoted through education and by simplifying environmental figures to formats readily understood by the public.	Acceptance has to be carefully thought through, by presenting carbon numbers in terms of savings percentages (e.g. a homeowner will save 17% of their bill rather than a homeowner will save 17% energy); prompting sustainability and resilience through social networking applications; and minimising the design requirements (i.e. no heating facility in the building).

[1] The commentaries for each of the scenarios were based on available information in the literature review and on Saudi Arabian construction industry practice.

5.2.5.2. (NC 2): Bounce-back ability of the building

The quantity of structural materials consumed is highest within the building sector (De Wolf et al., 2015). Therefore, it is understandable that structural materials play a vital role when considering the ability to reduce the environmental impacts of construction materials in general. Accordingly, the bounce-back ability (when faced with extreme conditions, for example) of the structure of the building is a matter of concern. There is always a need to carefully consider structural design requirements and balance these against proposed (alternative) sustainable solutions. The question asked should be *'Does the solution meet the minimum requirements now but also in the future?'* If the answer is yes, then that solution can be adopted with some level of confidence that its level of performance will not be compromised.

For example, when selecting a concrete mix with replacement cement, such as PFA or GGBS, a designer must choose the same compressive strength, so that the building can function as it was intended to. In this case study, the concrete mixes are 25–30 MPa and 28–35 MPa respectively. In an aim to cut costs and material use (two pillars of sustainability) the designer could suggest a solution that reduces the compressive strength or concrete sections, especially when the building structure is seen as overdesigned. This would reduce the negative environmental effects from concrete, but the designer must make sure that the building is safe and will function (carry the design loads) without any problems in the future – in other words ask whether, in an aim to meet sustainability goals, the resilience of the solution has been compromised.

5.2.5.3. (NC 3): Absence of other environmental considerations

Another proposal is to replace aluminium frames with PVC. PVC frames reduce in-use energy. They also have smaller embodied carbon and energy coefficients than Aluminium (i.e. Aluminium uses 155 MJ/kg and 9.16 $kgCO_2e$, respectively, whereas PVC uses 77.2 MJ/kg and 3.1 $kgCO_2e$, respectively). However, once again it needs to be questioned whether the resilience of the solution has been compromised. Granted related energy consumption criteria can be significantly reduced but just how might PVC be affected by the hot weather of Saudi Arabian summers? This also demonstrates that adopting a solution that works well in one context may not deliver the same level of performance when adopted in another. Referring again to Section 5.2.4, Alternative 4 with aluminium frames (with triple glazing) it can be see that this solution saves 30% of in-use energy and is better in terms of extreme heat resilience than Alternative 5 with PVC. What is important here is that decision-makers do not get too distracted by the targets in hand and chase these at the detriment of missing other environmental and resilience impacts.

Selecting Alternative 5 with PVC frames can still be considered a viable solution in cities such as Khamis Mushait and Abha, which have lower peak temperatures. However, the construction community might face difficulties implementing this change as plastic is known to be environmentally unfriendly in its production and is simply dumped at end-of-life; this alternative could be promoted if regulations attach a condition that only recycled PVC can be used in its production. Stichnothe and Azapagic (2013) concluded that the use of recycled PVC frames leads to a huge reduction in carbon emissions. The use of recycled PVC would therefore be a viable slightly modified, environmentally friendly solution.

5.2.5.4. (NC 4): Environmental footprint of transport

Maintaining the current environmental footprint for transport is an important necessary condition because at the design stage it was assumed that most materials would be from local manufacturers or suppliers (not least PFA). Regulating types of transport and enforcing the use of those with minimum carbon emissions is a solution, but unfortunately, this is not always within the control of the construction industry. If policy suggests that PFA and GGBS have to be adopted in concrete as a replacement for cement, whilst they might be supplied locally at the start, as coal-fired power stations reduce supplies, they may very likely be imported from farther and farther afield, inadvertently increasing carbon emissions. Becoming a net importer of any resource is not necessarily the most sustainable option and goes against the push for local provision.

Another issue confronted by designers is that the vast majority of materials (excepting steel) are disposed of after the end of the building’s life. In the future, most materials, including blocks, ceramics and so forth should be more readily recycled / reused / repurposed when a building nears its end-of-life in order to maximise sustainability benefits; hopefully, there are not long-term implications of using PFA and

GGBS within concrete. These transportation and recycling requirements would need to be considered for all materials adopted.

5.2.5.5. (NC 5): Minimum building code requirements

When it comes to regulations, including building codes, certain U-values for building elements should be set, for example, by setting a maximum level (or Grading performance A to E) for embodied carbon of materials and so on. These measures will add positive value to utilising the RESAF framework itself, so that users will aim to achieve these requirements to meet (and exceed) minimum performance. In the resilience context, complying with regulations is not just meeting minimum requirements; it is also ensuring that designers continue to abide by and ultimately willingly exceed these minimum requirements.

Referring back to Section 2.5.2.2, nowadays, copy of relevant codes (SBC (602) and SBC (1001)) are readily available. Hence a validation of the case study results will be conducted in a line of this code in Section 5.4.5. However, concerns still exist, firstly regarding resilience not being a part of the code agenda. The key concern is why the sustainability and resilience are not merged in one code. Marchese et al. (2018) discussed that two separate objectives for sustainability are misleading, such that efforts result in "conflicts and underperformance". Secondly there is concern that the absence of including a materials' environmental effects within the code, in particular embodied carbon and energy for materials. The code only considers the in-use energy for the long-term performance of the building, this might be considered a shortfall for 'actual' sustainable performance.

Whilst Bakhoum and Brown (2012) stated that if the levels of sustainability are to keep improving in the future, assessment and continuous improvement are essential. Consequently, it is fair to say that the engineering and construction community needs to work much harder to ensure the promotion of sustainability in work practices. A gradual enforcement of the regulations is a good approach to making the rules easy to follow, practical and enduring.

5.2.5.6. (NC 6): Public acceptance of sustainable solutions

The final issue is the ability of the public to accept these proposed solutions. It is sometimes difficult for people to change their behaviour – the status quo often prevails. For too many years people have built their houses using normal concrete or single and double glazing, and whilst a designer might suggest alternatives, decisions can be heavily influenced by other key drivers, including cost. The role of designers is to highlight the short- and long-term benefits (including cost reduction) in relevant graphical figures and tables. The role of the RESAF user or a designer is important to transfer savings to reality, meeting the client's requirement. A key to this is promoting sustainability through easy language that potential homeowners (clients) can understand.

For example, designers might translate the yearly energy savings (kWh/yr) into a percentage of the homeowner's electricity bill (see Section 5.5.1.3 for energy cost). Increasing awareness of sustainability among the local community is also a necessary major change in order to implement sustainable and resilient buildings. The designer may not need to adopt a heating system but just use the cooling system in the building because in some cases, the heating loads are too low (see an example in Section 5.2.3, p. 137). However, designer justification and people's (i.e. homeowner's) requirements are key.

One way to increase public awareness is to better use the media to introduce the Saudi public to the concept of sustainability (Susilawati and Al Surf, 2011). Additionally in the present environment, stakeholders might more readily promote the benefits of improved sustainability and resilience thinking through social networking applications.

5.2.5.7. (NC 1 to 6): Necessary (resilience) conditions overall

Referring back to how to demonstrate the maximum sustainability benefits in the future, it is more about thinking of future sequences of decisions made in an early design stage. Once these benefits have achieved overall acceptance, then decision-makers/practitioners (e.g. designers, engineers, contractors) can go with what might be called a modified design or proposed solution. To be clear, a modified design is one that has been processed (and passed) through both sustainability and resilience filters. In all necessary conditions presented, there are always other considerations to help the future-proof-ability of the solutions. Tables 5-10 and 5-11 show how this might play out within the three archetypal futures previously described. This is not intended to be an exhaustive list although it does include key elements. Therein it can be seen that the following considerations should be taken into account:

- Offer more alternatives when regulating / proposing specific materials (i.e. not just regulating PFA and GGBS as cement replacements);
- Design minimum requirements (i.e. strength in structural design) that need to be achieved to attain structural performance (in a changing climate);
- Consider other environmental effects on alternative material options, such as hot weather in countries such as Saudi Arabia (i.e. plastic materials as a replacement for aluminium could have other negative effects);
- Expand the building codes to set clearer target benchmarks (i.e. U-value requirements);
- Transport is not controlled by decision-makers / practitioners, but effort could still be made (i.e. minimise transport of materials where possible); and
- The public's overall ability to adopt changes is a matter of concern – education and information are key criteria here.

5.3. Validation part 1 - Interview results

The interviews provide a level of professional validation and critique for the project and accompanying developed RESAF. See Section 3.2.3 for a general description of the interview process and Section 4.6 for a specific description (outline, questions, the selection criteria of the participants and details of participants, including profession, organization type, level of education and years of experience). Full interview scripts for the participants' responses are provided in Appendix C, Tables 1 and 2 – additionally, a discussion of the feedback on the project's interview section is in Appendix D.

5.3.1. Feedback on the framework (b)

The purpose of this interview section is to assess the validity, relevance and ease-of-use of the RESAF. Figure 5-8 presents agreement responses to statements considering the RESAF beta version input, output and user manual.

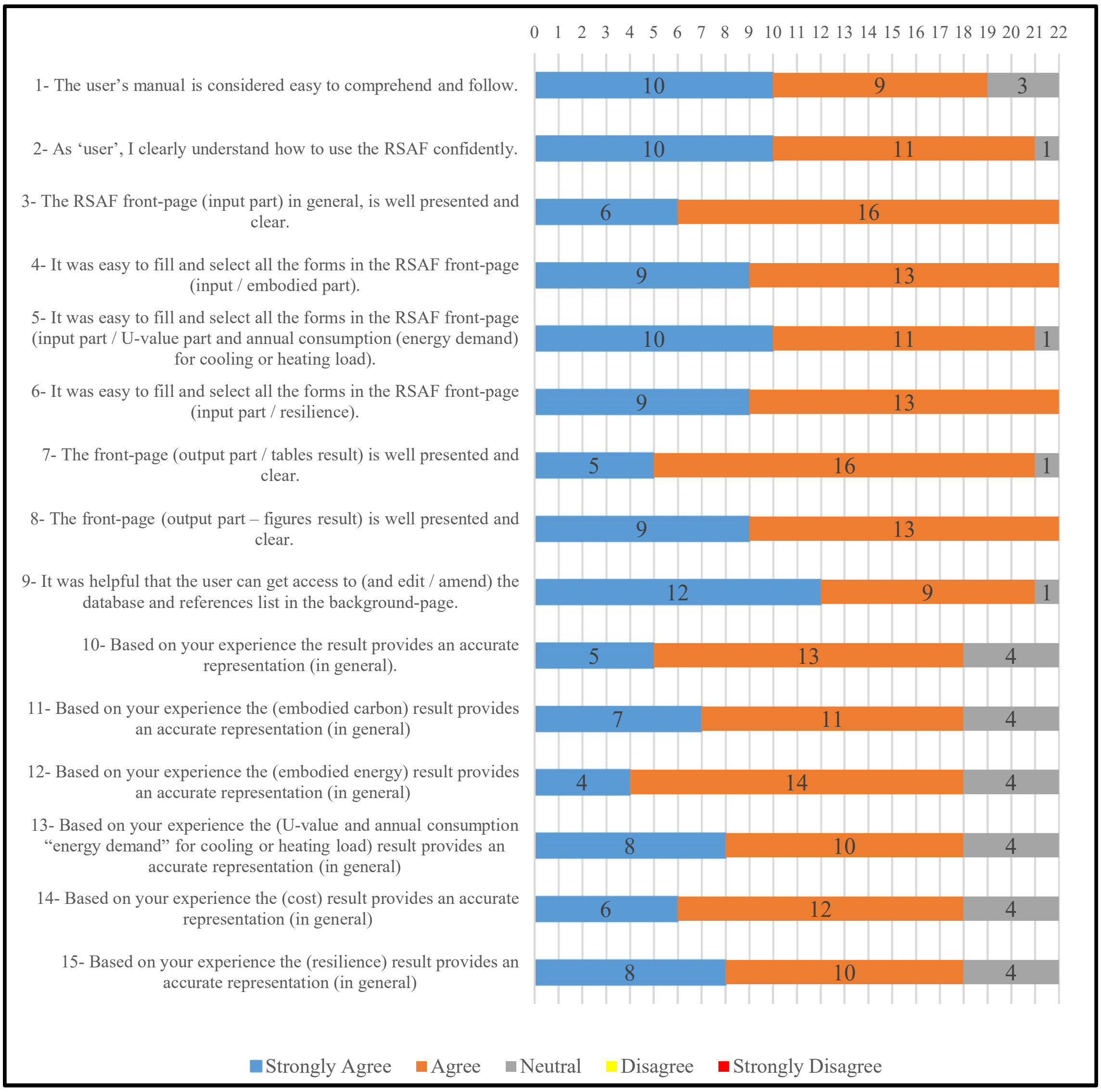


Figure 5-8 Rate of agreement with the RESAF (beta version)

The RESAF beta version gained favourable feedback in terms of the rate of agreement with most answers (strongly agree and agree). Using the RESAF and the input parts (points 2 to 9) received very high agreement by the interviewees. This is very important when designing a framework, as it means they were able to use it and understand the input parts clearly. This is a good sign, assuring that such a framework can be smoothly implemented by potential industry users.

With respect to the user manual (Point 1) and the results (points 10 to 15), the feedback again was mostly confident. There was positive feedback that mentioned the user manual; one interviewer stated that it was an important consideration that the references were included in the user manual. However, a minority (3 or 4 out of 22) of interviewees selected neutral in response to the RESAF results and user manual, which was expected if the interviewees were not able to reach a decision. Most likely the reason was that the interviewees were not in a position to verify the results and data themselves or were not able to go through the entire user manual due the limited time for the interview.

Ten interviewees answered no and 8 answered yes with respect to whether the RESAF is missing information (see Figure 5-9).

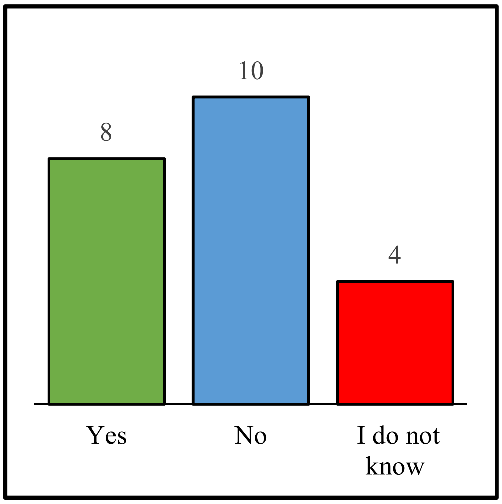


Figure 5-9 Based on using the framework, is there any missing information?

There were some suggested areas of improvements, a summary of which is in Table 5-12. Actions and justification have been presented at each point. These have been reflected in the RESAF (see Section 5.5).

Table 5-12 Suggestions and actions for RESAF

Comment No.	Participant No.	Suggestions	Responses
1	14	*'I would suggest to specify the cost to the operation cost instead'*.	The building in-use energy operation cost was included based on this suggestion. An improvement was also made to the existing cost, which relates to the cost of energy for materials. See Section 5.5.1.3
2	2	*'Simplify the results to be per m^2', 'This framework is for experts' and 'Can the non-expert use it?'*	-The presentation of the results was simplified based on this suggestion. A separate page called "key results" was created (see Figure 5-13), the purpose of which is to summarise the important outcome as simplistically and briefly as possible. -The interviewee suggested this for a non-member of the construction industry. To clarify this, the framework is designed to be used by people who work in the construction industry. At this stage, there are no plans to make it accessible to users outside of the industry. However, it is recommended that the user explains the benefits of the proposed materials to their clients (see Section 5.5.1.1).
3	16	*'The user manual could be improved'.*	The entire user manual, and especially its presentation, underwent a general revision following the validation process.
4	7	In terms of the user manual: *'The reason behind creating such [a] framework and its position among other frameworks'.*	This information was revised within Section 1.1 in (the user manual document)
5	21	*'Unit selection. It is good to have an option of unit selection (metric – imperial)'.*	In Saudi Arabia, the metric system is used, and giving the user two options will not add value to the RESAF.

6	21	*'A full report can be generated from the Excel software'.*	The presentation of the results in the output part was revised. See point 2.
7	17	Geographic Information System (GIS) to be included, such as land use and conditions.	A map of Saudi Arabia has been included for the location within the RESAF. Soil type is already in the scope of the framework for the underground U-value calculation, but the user is responsible for selecting the type, as each building location will have a different soil type, even if it is in the same city.
8	15	*'Just if a Saudi data input can be added to the framework, which could be organized with SASO and/or individual Saudi companies that supply construction material'.*	Unfortunately, data are not available. Several attempts have been made with stakeholders, but no data were released.
9	11	-Information or data about the design stages and alternatives. -Explain the alternatives materials (friendly and non-friendly).	A new section in the user manual was added to demonstrate this. This section explains how the user can improve the design performance.
10	11	Add green materials because they benefit the environment as they absorb carbon and reduce heat (i.e. they are used as insulation in some countries).	Using a green roof (vegetation cover) is not a sufficient action because of the high temperatures in the country.
11	19	Building a life cycle that is preferably longer than 50 years.	An option has been added; therefore, a better overview of the building life can be obtained. However, one year of energy use will still be the main consideration.
12	18	Not including other building effects, for example lighting.	This is out of the original scope, as the research is focused on material effects. This could be one of the future works (see Section 6.5.).

13	20	No input about constructing stage, although it has a minor effect.	This is out of the research's scope, based on the work of Heravi et al. (2016), in which the construction stage within the LCA is not concerned with the energy consumed.

All 13 comments suggested minor revisions and do not reflect the results and the RESAF methodological approach. Generally speaking, interviewees requested the inclusion of extra aspects or more clarification in terms of improving the RESAF presentation. Ten out of 13 comments resulted in revising the study accordingly. The other three comments were not applicable and therefore did not create any revisions. Comment 5 is not applicable to the Saudi Arabian context, while comments 12 and 13 are out of the study's scope.

In the published research database, searches specifically for Saudi Arabia and the terms "embodied carbon", "embodied energy" and "thermal conductivity" are not available, although a number of people working in the field suggest that some data (not all) might have been developed but not published by organisations in Saudi Arabia) see Figure 5-10). A study by Asif et al. (2017) stated there was a localised absence of the data with respect to construction materials.

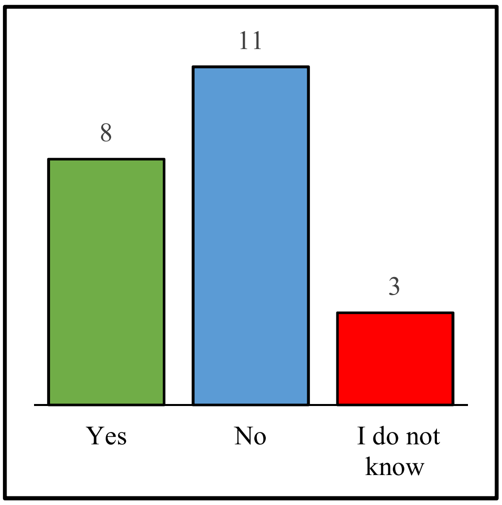


Figure 5-10 Do you have or know of any suggested references that consider Saudi Arabia more directly?

The researcher's perspective about this is that data should be presumed to be unavailable, because if the data were accessible, they should be produced in publication formats, which is not the case here. It is recommended that the data be produced by organisations or researchers in the Saudi Arabian context; See section 6.5. for Recommendations and Further work.

On the future of RESAF implementation, 20 out of 22 people confirmed they will use the developed framework in their work (see Figure 5-11).

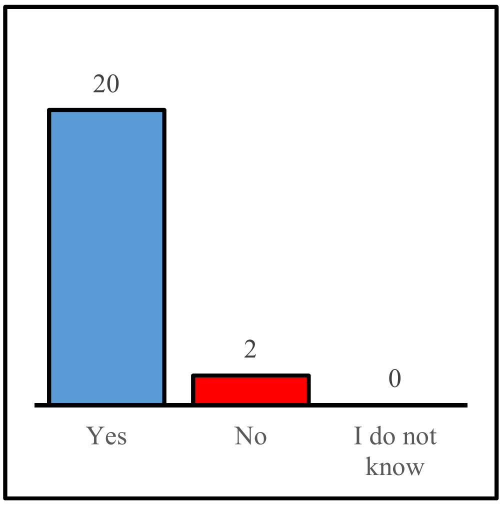


Figure 5-11 Would you use the proposed framework in your work?

One interviewee (No. 8) reasoned, *'Any tool that can help understand the selection process of materials and its impact on sustainability is welcome'*. Lending further support, interviewee (No.15) said, *'I think it will provide a strong case to prove how much details [of] the sustainability and resiliency of a building can be in [a] quantitative and referenced platform and not just quantitative and theoretical'*. In principle, the quantitative approach is an advantage because the framework user will obtain an environmental assessment result in the form of energy and carbon numbers and figures. The user will have a chance to grade future scenarios in terms of necessary conditions. Another interviewee (No. 2) said, *'Try to help you even in a simple way'*. It is not surprising that a user might not want to implement the RESAF fully and instead have an overview of the RESAF results.

Of the two interviewees (Nos. 7 and 13) who stated "I do not know", one (No. 7) said, *'It depends on the case [and] its location and conditions'*. Again, it is not surprising that such a new framework will be used in a case-by-case situation. Thus, revising the RESAF presentation and putting more effort into the credibility is one solution for creating a better experience in terms of results and usage.

Section 5.5 includes a detailed explanation of what has been revised in the RESAF with respect to the actions listed in Table 5-12 and the sequences of the interviews validation in the RESAF outline and user manual.

5.4. Validation part 2 - Comparison results

A number of benchmarks in Section 4.7 had to be addressed against the RESAF results; this was done by comparing them to other studies, as justified in the following sections.

5.4.1. RESAF outline

The scope of this RESAF is wider than that of former studies that targeted domestic buildings in Saudi Arabia (see Figure 3-2 and Table 4-1). It includes a range of assumptions that are well-grounded in the literature review. The RESAF considers many key environmental concerns, such as the annual energy demand and related carbon footprint for the cooling or heating load (which is the important part of energy consumption during building use), as well as the materials used to construct the building, with an assessment of their embodied energy and carbon. The RESAF explains how different materials will contribute to the in-use energy of the building and the negative environmental effects of the materials themselves.

The study developed this framework to address the shortcomings of previous studies that used aspects in isolation rather than in combination. Brief examples of past studies include the following:

1- A cradle-to-gate assessment of embodied carbon and negative effects on the environment that included the global warming potential (GWP) of the materials utilised for a housing project in Saudi Arabia (Asif et al., 2017);
2- An assessment of the energy consumption (during operation) used for a domestic building (Alaidroos and Krarti, 2015a; Felimban et al., 2019; Taleb and Sharples, 2011; Alaidroos and Krarti, 2015b) in Saudi Arabia;
3- Establishing a standard definition for low energy demand in the form of kWh/m^2 for domestic buildings in Saudi Arabia (Aldossary et al., 2017); and
4- A lack of insight in to the important considerations for the resilience of sustainable solutions proposed, specifically in terms of uncertainty in the future

and how these solutions will perform, which has not been broadly discussed in Saudi Arabia. Although resilience in Saudi Arabia has been studied (Alshehri et al., 2013a; 2013b; 2015a; 2015b) and a framework for community resilience to disaster has been proposed, it was not directed at buildings, which this RESAF focusses on.

In short, dealing with a number of environmental materials issues together provides reasonable solutions for these issues, especially the advanced step in the RESAF, which maintains how these solutions could cope in the future.

5.4.2. Materials and their embodied effects

Only one identified study, by Asif et al. (2017), conducted (cradle-to-gate) an LCA assessment for a house building in Saudi Arabia (see Section 2.3.1). The RESAF and the previous study shared a number of key findings. One such finding was that the concrete material had the most significant remarkable energy consumption among other materials. Steel was second in terms of energy consumption. However, there are key differences between this study and that conducted by Asif et al. (2017) in assessing the LCA of materials. First, Asif et al. (2017) does not provide alternative materials that have low environmental effects; however, this study provides a framework by which alternatives can be identified and assessed. Secondly, the environmental effects from transporting materials from gate-to-site are extended for the RESAF, in contrast with Asif et al.'s study (2017), where these are excluded. These give an advanced image of the materials' environmental effects in RESAF, which also explores alternative solutions.

If the framework material results had been generalised and other non-Saudi Arabian studies consulted, one could see that the building structure materials have the biggest influence in terms of raising the carbon footprint. Webster et al. (2012) and Kaethner and Burridge (2012) indicate that on average the carbon footprint from the structure of a building represents higher than half of the total, an indication that was cited after De wolf et al. (2015). Moreover, a study by Häfliger et al. (2017) that modelled houses using LCA in Switzerland concluded that high priority is given to concrete and masonry among other materials when the purpose is to reduce the negative environmental footprint of buildings. In the Saudi Arabian housing context, the building structure consists of steel reinforced concrete. Within the RESAF case study, a total of around 58% of the carbon footprint is from the ready-mix concrete (46.94%) and steel reinforcement (11.51%). The studies by Asif et al. (2017), De wolf et al. (2015) and Häfliger et al. (2017) validate the findings of the importance of building structure in construction materials' negative environmental effects.

5.4.3. Energy consumption during the building's operation

A limitation noted is that in terms of energy use during the operation, RESAF only calculates cooling and heating energy. The reason for this is the significant impact of energy cooling demands in Saudi Arabia. A number of studies stress the energy cooling loads' significant accountability in the country. For example, in the summer season, cooling systems currently account for around 66% of household electrical demands (Krarti and Howarth, 2020). A yearly modelling of electricity demands also shows that a house consumes 67% for cooling loads, 3% for heating loads and 4% for fans loads in Dhahran city (near Dammam city – the main RESAF case study) (Alaidroos and Krarti, 2015b). Therefore, the cooling and heating loads show a fair expectation of energy use through the building operations.

Comparing the results of in-use cooling energy with those of Alshahrani and Boait (2019) for cooling energy consumption, a different residential building in Riyadh city consumes from 167 to 246 kWh/m^2/yr according to simulation software. A RESAF original design consumes around 181 kWh/m^2/yr; therefore, it is well within this range. Another study by Alaidroos and Krarti (2015b) claimed that a house in Riyadh consumes around 160 kWh/m^2/yr for cooling and heating loads, compared with 196 kWh/m^2/yr from this study. Although it is a bit higher in the RESAF case study, this is normal, as the criteria of the calculations, simulations and design properties are different, which results in a slight difference in the expected in-use energy.

Past studies confirm that the in-use energy RESAF results are reliable and give a reasonable expectation of figures.

5.4.4. How buildings will meet sustainability / resilience requirements in the future.

None of the past studies reviewed the resilience at a building level, particularly in the sustainable buildings area (See Sections 2.4 and 2.5). Regardless, this section looks at the studies to see whether the proposed solutions and recommendations in sustainable domestic buildings can be considered for the future. Most importantly, this section checks that the RESAF necessary conditions are sufficient or that there are conditions from past studies that can be covered.

The studies by Taleb and Sharples (2011) and Aldossary et al. (2017) put forward a number of recommendations linked to policy formatting, building occupants' promoting and engineers' education in sustainable housing. These issues have been covered in the necessary conditions for minimum building code requirements and have been accepted by the public as sustainable solutions.

The phrase *'User behaviour on energy'* appeared in a study by Felimban et al. (2019). Behaviours of the house occupants or designer clients, of course, play a role in the future of the RESAF. Again, this has been publically accepted as a sustainable solution to implement in their homes. This has been also addressed in the absence of other environmental considerations, such as when PVC frames proved to reduce energy for cooling, but one of the issues was that it is a well-known non-environmentally friendly option in terms of its use of plastic.

Referring back to Section 5.4.2, Asif et al. (2017) recommends exploring *'environmentally friendly materials'*, which the RESAF covers. The RESAF user can reduce the embodied impacts of materials, as there are a number of material options available within the RESAF. For more advantages of these materials options, a condition of availability of proposed material was part of resilience assessment. See Table 5-10 (NC 1) for an example; here, it discusses replacing the cement used in ready-mix concrete with PFA or GGBS to reduce embodied carbon and energy.

In past studies, proposing sustainability and the environmental footprint of transporting materials, other conditions have not been recommended for the future of sustainability. In summary, past studies often made recommendations but never applied them beyond presenting them in a detailed discussion. Studies did not consider how solutions would perform in the future. There is a difference between recommending solutions and assessing the future performance of solutions, which might (and perhaps should as is done within RESAF) include recommendations as part of the assessment.

5.4.5. Guidance on available regulations in Saudi Arabia

This section reviews whether the RESAF complies with the related available guides in Saudi Arabia, specifically, as represented in Section 2.5.2.2, the Saudi Energy Conservation Code – Low-Rise (Residential) Buildings (SBC 602) (SBC, 2018a) and Green Building Code (SBC 1001) (SBC, 2018b). Although these are in the early stages of development, they will be consulted. The factors that the case study should comply with are shown in Table 5-13.

Table 5-13 Saudi building code factors and RESAF case study

No	Code	Factors	RESAF case study
1	SBC 602 and SBC 1001	Windows area illustrates a maximum of 25% of the wall gross area, and 3% for roof lights. The original design meets this requirement with less than 10%.	The original design meets this requirement with around 11%. Case study windows are 133.20 m^2 (11%), and the wall gross area is 1253.20 m^2. There were no roof lights in the case study.
2		Maximum U-values: Windows: 2.668 W/m²K	The original design meets this, as it is 2.5 W/m²K for double glazing. Although, the proposed solution is to use triple glazing as it is 1.9 W/m²K for an aluminium frame or 1.6 W/m²K for a PVC frame.
3		Maximum U-values: Roofs: 0.31 W/m²K Walls: 0.53 W/m²K	The original design does not meet these requirements; however, the RESAF was able to meet this with minor changes, see Tables 5-7, 5-8 and 5-9.

It is clear that these factors largely depend on the user selections and house building design. These factors are included in the user manual, so the user can easily follow its guidance.

5.5. Discussion

5.5.1. The influence of the validation step to come up with a final RESAF version

There are a number of suggestions in Table 5-12 that this section addresses, along with other discussed points.

5.5.1.1. Results of the RESAF application as well as user manual presentation

The front page of the environmental results can be seen in Figure 5-12. To shape up the sustainable environmental results, and to have them be in line, on a separate page, a new section called key results was created (see Figure 5-13). The main function of this page is to summarise the results in a simple and brief way.

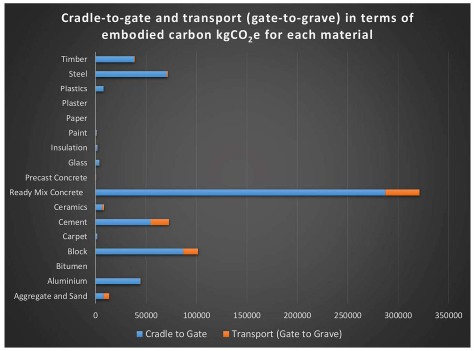
RESAF now demonstrates the embodied materials' effects by using numbers and percentages in diagrams for the cradle-to-gate in $kgCO_2e$ and MJ, and the gate-to-grave for transportation in $kgCO_2e$. Moreover, in-use energy for cooling and heating demands and its carbon footprint have now been presented annually per m^2, as well as the total annual consumption. A building's life, averaged at 50 years of in-use energy, and its carbon footprint have been added in an extra chart to help users who are interested in this information.

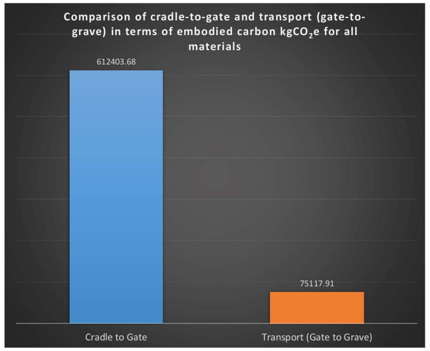
The detailed results will still be included on the main RESAF page so users can still work based on their preference if they need to look into detailed results.

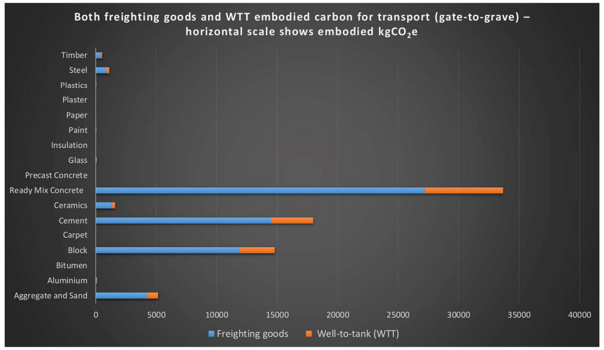
Figure 4-6 outlines and explains the purpose of the user manual. After the interview process, the outline did not change; however, the document presentation was revised for edition improvements (see Appendixes F and G for beta and final versions, respectively). Additional parts have been covered. The RESAF's purpose and its position among other tools and frameworks are described in the overview section of the user manual. Tips (summarised examples) for how to use the RESAF to improve the environmental effects and the resilience assessment have also been included in the user manual.

Results (output)

Summary graphs







Summary tables

Material	Embodied kgCO$_2$e	Embodied kgCO$_2$e	Embodied energy (MJ)	Embodied energy (kWh)	Energy cost (£) - Saudi Arabia	Energy cost (£) - United Kingdom
	Cradle to Gate	Transport (Gate to Grave)	Cradle to Gate	Cradle to Gate	Cradle to Gate	Cradle to Gate
Aggregate and Sand	8154.85	5139.82	128595.52	35721.26	1321.69	4211.54
Aluminium	44270.28	94.41	749115.00	208089.16	7699.30	24533.71
Bitumen	0.00	0.00	0.00	0.00	0.00	0.00
Block	86715.65	14784.62	841503.52	233752.85	8648.86	27559.46
Carpet	1483.68	26.21	26829.66	7452.74	275.75	878.68
Cement	54641.59	17978.17	328838.51	91344.76	3379.76	10769.55
Ceramics	6629.22	1594.39	101988.00	28330.23	1048.22	3340.13
Ready Mix Concrete	287434.18	33676.53	1845880.38	512748.65	18971.70	60453.07
Precast Concrete	351.90	31.70	2831.85	786.63	29.11	92.74
Glass	3577.50	77.57	62275.00	17298.75	640.05	2039.52
Insulation	1748.70	12.02	47092.67	13081.40	484.01	1542.30
Paint	983.00	33.93	23646.00	6568.39	243.03	774.41
Paper	0.00	0.00	0.00	0.00	0.00	0.00
Plaster	0.00	0.00	0.00	0.00	0.00	0.00
Plastics	7810.04	41.84	163212.98	45337.30	1677.48	5345.27
Steel	70516.51	1109.76	954247.56	265070.89	9807.62	31251.86
Timber	38086.59	516.92	521154.55	144766.31	5356.35	17067.95
Total	**612403.68**	**75117.91**	**5797211.19**	**1610349.32**	**59583**	**189860.19**

Figure 5-12 The main results on the RESAF home page

Figure 5-13 The new page for environmental sustainability results

5.5.1.2. RESAF contribution to selecting appropriate materials

The RESAF considers three main key concerns:

(1) The annual energy demand and related carbon footprint for the cooling or heating loads (the important part of energy consumption during building use);

(2) The materials used to construct the building and assessing the embodied energy and carbon. It explains how different materials will contribute to both the in-use energy of the building and the negative environmental effects of the materials themselves;

(3) The RESAF also demonstrates how these materials (and the proposed changes to them) have been assessed in the context of the necessary resilience conditions, such as the availability of proposed materials or public acceptance. This is because it is important to understand how these selected materials (the proposed solutions) are fit-for-purpose in the future.

To sum up, this is the story of the RESAF case study application and how the original plan improved by making technical changes to the materials proposed. For example, the following changes were presented:

Alternative 4, as listed in Table 5-9, suggests

- replacing the cement with 50% blast furnace slag when using ready-mix concrete,
- replacing autoclaved aerated blocks with concrete blocks (8 MPa), changing insulation type and thickness, and
- replacing the double glazing with triple glazing and keeping the aluminium frame.

By doing this, around 22% of the embodied carbon for materials was reduced, and 30% of the carbon during the in-use stage was reduced in the yearly building life.

Then, a resilience filter proves the future-ability in many terms, such as ensuring more cement alternatives are included and that the structure design is respected, etc. All these processes are expected to be followed by the RESAF user, who will be able to explore a number of alternatives and select the suitable alternative that meets the design needs.

The impact of savings in energy consumption and carbon footprint is not reflected in the house itself, but it will maximise the overall benefits at the community level. Imagine these reduction figures applied to numerous houses: the savings will be incredibly large, especially when applied to a city or a number of cities. This will definitely reduce the demands of electricity from the domestic sector, which in Saudi Arabia is 43% of the overall electricity demands in the country (General Authority for Statistics, 2018a).

When the RESAF was in the beginning of its design, a set of seven requirements (shown in Table 3-1) were considered to comply with, as established by Laurentiis (2017). Tables 5-14 and 5-15 list the justifications of how the RESAF and its user manual meet these requirements. One of the vital points for all these requirements is that the RESAF and its user manual go through a validation process by experts in the country.

Table 5-14 RESAF requirement justifications (1-2)

No	Requirements	How these points are achieved
1	Contextual applicability	- The RESAF covers materials that are ordinarily used in the building construction industry in Saudi Arabia, such as concrete and block materials. - It also covers a wide range of cities; a total of nine cities are covered, representing the three thermal climatic zones in Saudi Arabia. - The RESAF also fills the gaps in the industry, being a framework that can help to choose appropriate construction materials.
2	Usability	A user manual was created with a case study demonstration to ensure it is a user-friendly experience. In Figure 4-6, the user manual is outlined, as well as how it is presented. A user manual (final version) is in Appendix G.
3	Meaningfulness	Units that are familiar to building practitioners were used within RESAF (i.e., kg, m^2, kWh, MJ or/and $kgCO_2e$). A simplification of the results has also been shown (per m^2) to ensure clarity, such as with kWh/m^2. .

Table 5-15 RESAF requirement justifications (2-2)

4	Adequate completeness	It covered materials and their embodied effects, as well as their effects during the building operation and how they will perform in the future.
5	Validity	Experts in the Saudi building industry were consulted, and the RESAF gained overall acceptance. Their feedback and comments were addressed to produce a final RESAF version.
6	Transparency	The user manual provides basic calculations (user manual – Section 2.2). For more information on the RESAF design, see sections 4.2 and 4.3. Basic data and references are accessible to users (pages Data, Data 2 and Data 3 in the RESAF Excel application).
7	Adaptability	The RESAF data (pages Data, Data 2 and Data 3 in the RESAF Excel application) are adaptable. The user manual contains an explanation for how users can make these adaptations (User Manual – Section 2.2.6).

After the building practitioners come up with proposed solutions using RESAF, they may look to resolve the cultural resources versus sustainability conflict. The following can be done:

- A number of studies linked cultural resources in Saudi Arabia with house design considerations, such as privacy, family size and dynamics (e.g., large and close knit), room sizes and locations of the rooms within the building (Opoku and Abdul-Muhmin, 2010; Alyami et al., 2013; Aldossary, 2015; Al Surf, 2017). In terms of construction material choice, this is more of ensuring house owner satisfaction and safety (Bakhoum and Brown, 2012), such as ensuring that when structural materials change, the building structure can still function as intended (see Section 5.2.5.2);
- Building practitioners may involve the house owner in the design decision, particularly when applying RESAF, to ensure that the house owner's requirements are met. This will also help increase public unawareness of the advantages of building sustainable houses (i.e., changing material choices for home energy savings) (Al Surf and Mostafa, 2017) (see Section 5.2.5.6).

Building practitioners may suggest solutions to be applied during the building operation, such as using a smart AC thermostat (room temperature) to prevent the AC from working for long periods of time (Alshahrani and Boait, 2019); and

- Building practitioners should also ensure that the material choices are in line with what is currently used in Saudi Arabia (see Table 2-8 in Section 2.2, which shows that the main material used to construct housing units is concrete, followed by block/brick). In the proposed materials solutions, for example, replacing a percentage of cement with PFA and GGBS was proposed when using concrete in building construction, instead of changing the concrete materials with completely new ones.

A recommendation of a customised, new version of RESAF that targets non-expert users (potential house owners) is a further development of the framework (see Section 6.5). The current RESAF version targets only those users who are building practitioners or those interested in the building field (see Section 6.4).

5.5.1.3. Energy cost

The cost of in-use energy was originally not in the scope of this study (see Table 4-1 and Figure 4-1). Despite this, the cost was ultimately included (albeit superficially and not for all aspects of material selection) after one of the interviewees suggested giving an overview of how much a household could save (in terms of running costs) when using the RESAF. From the beginning of 2018 in the Saudi Arabian residential sector, the cost is calculated on a monthly basis, which is 0.18 Saudi riyals/kWh (0.036£/kWh) for the first 6000 kWh, then increases to 0.30 Saudi riyals/kWh (0.060£/KWh) (Saudi Electricity Company, 2018).

The energy cost is applied to the proposed alternatives in Table 5-9. Therefore, an average monthly bill for these alternatives is presented in Table 5-16. This table reports tangible monthly savings of 36% and 38% for Alternatives 4 and 5, respectively, especially when it is assumed that these savings will last for several years of the house's life. The actual cost of energy is not fixed and might be changed by relative bodies in the country, but the drive is the percentage of savings with respect to the average monthly bill.

Table 5-16 Cost of the proposed alternatives

Aspects	Yearly energy consumption (in-use stage)	Cost of monthly in-use energy for cooling and heating (£)
Base case	176,295 kWh (198 kWh/m^2/yr) (no savings)	742
Alternative 1	176,295 kWh (198 kWh/m^2/yr) (no savings)	742
Alternative 2	145,792 kWh (164 kWh/m^2/yr) (17% savings)	588 (21% savings)
Alternative 3	142,266 kWh (160 kWh/m^2/yr) (19% savings)	571 (23% savings)
Alternative 4	123,510 kWh (139 kWh/m^2/yr) (30% savings)	476 (36% savings)
Alternative 5	119,984 kWh (135 kWh/m^2/yr) (32% savings)	459 (38% savings)

5.6. Summary

This chapter presented the RESAF case study results and how to select the construction materials (replace the materials) to minimise the environmental effects (embodied energy and carbon) in line with the resilience in the context of three very different future scenarios: Market Forces, Policy Reform and the New Sustainability Paradigm.

Then, these results went through a validation process via expert consultation (the interviews) and past studies were consulted. Finally, a discussion was presented in both the validation step and the RESAF contribution to materials selection.

The conclusion is drawn in the next chapter, which also states the limitations of the framework and outlines recommendations for future work in relation to this study.

6. Conclusions

6.1. Introduction

This chapter concludes the research study. Section 6.2 summarises the research study in line with the aim and objectives originally set and methodology stages conducted in order to achieve these. The value of the study and its overall contributions towards filling the gap in knowledge identified are addressed in Section 6.3. Limitations of the study are outlined in Section 6.4, in particularly with regards to the scope of the RESAF. Finally, Section 6.5 provides recommendations for related stakeholders, as well as suggestions for future study in the context of RESAF.

6.2. Summary of the study

This study has shown how to assess more holistically the choices we make when it comes to material selection for domestic homes, with a particular focus on, but not limited to, Saudi Arabia. With minor adjustments (e.g., addition of new data for construction materials), though, RESAF could also be used for other countries. RESAF provides a significant advantage over existing systems in that once the iterative process of making environmental improvements has been made, alternative material solutions can be passed through the resilience filter to identify their potential to achieve longevity of use, whatever the future might hold. This allows the resilience of the solutions to be considered more readily so the long-term impacts of the choices can be highlighted using a range of archetypal future scenarios (i.e. Policy Reform, Market Forces and New Sustainability Paradigm), this included, but is not limited to interrogating the availability of materials, including PFA and GGBS, in the far future and the durability of these alternative materials in extreme heat. RESAF was also assessed (i.e. pressure tested using a user group) to identify its validity, relevance and ease-of-use for the beta version of the framework tool.

This study was drawn from the Objectives set in Section 1.2. These have been achieved, although as with any research there is always more that could be done given enough time and budget. In brief the research has achieved the following:

- An extensive systematic review of existing studies has been undertaken in order to identify the gap in knowledge that exists – this is related to integrating the sustainability and resilience of construction materials into Saudi Arabian domestic buildings;

- The RESAF framework has been developed – this was designed to assess the wide range of construction materials used in Saudi Arabia and to assess building cooling and heating during operation with respect to energy and carbon embodied. The data referred to and formal calculations used are presented and critiqued;
- The RESAF has been applied to the real design of a domestic building in Dammam (zone 1) to test the tool and assess how improvements for resilience and environmental sustainability can be achieved within the field of material choice adopted in domestic homes in Saudi Arabia. Additionally the impact of changing to other major cities (covering all three thermal climatic zones) in Saudi Arabia has been considered allowing for the local condition and local context aspects of sustainable material choices to be assessed;
- The RESAF's overall design and ease of application has been pressure tested using a range of experts in the field and its usefulness and validity (based on a Saudi Arabian context) has been confirmed. Additionally the case study outcomes have been sense checked via consulting experts in Saudi Arabia and compared with existing studies to compare /contrast results – the RESAF performed extremely well when put into this scrutiny;
- The RESAF and user manual have been amended and finalised from the beta version after being subjected to the validation process. This has allowed for user buy-in to be achieved. A necessary element of getting the tool adopted and used in Saudi Arabia, a pre-cursor to making step-changes in revolutionising the way materials are chosen.

This study draws the following conclusions:

- By reviewing past studies, it has been identified that there have been major challenges to achieving a standardised sustainability and resilience assessment. Therein the fact that every discreet assessing body has a particular procedure for determining environmental sustainability and resilience, each includes a plethora of locally derived indicators, metrics and benchmarks. It concluded that there was a need for a framework to be developed for a Saudi Arabian context that better reflected its local conditions. Moreover it was identified that there was a need to focus on building materials (those that are adopted traditionally and those that could be adopted in the future) and to understand better how material choices therein impact upon environmental sustainability and resilience concepts. It was identified that building materials in Saudi Arabia are a leading consumer of energy (not least embodied but also in use) and therefore have a huge environmental impact both before, during and after construction has taken place; therein with careful consideration significant carbon reductions can be achieved through appropriate material selections. What is important here is that options that might score highly in terms of environmental sustainability and receive accreditation through existing assessment frameworks may not suit the local context of Saudi Arabia …and may not provide resilience into the future given the local context and conditions of an arid/semi-arid region such as Saudi Arabia;

- The RESAF was designed to integrate two main approaches/tools: Firstly, an outer 'sustainability' filter simplified LCA (measures kgCO_2e, MJ, and kWh), which includes calculations and criteria tables. This filter paid attention to the concept of ecology (directly and indirectly impacted through carbon emissions) in order to minimise the negative effects on the energy demand and carbon footprint. Secondly, the inner 'resilience' filter Urban Futures Assessment assesses resilience aspects and is concerned with the long-term impacts of the material when considering necessary conditions in Tables 5-10 and 5-11;
- A case study application of the RESAF tool has shown that minor changes to building material selection (i.e. replacing cement with PFA or GGBS; see Table 5–9 for the five proposed alternatives) can play a vital role in reducing the materials' embodied energy (over 13%) and carbon (by > 23%), as well as building cooling and heating energy demand (by > 32%). It is also worth noting that gate-to-grave transport practices accounted for approximately 12% of the embodied kgCO_2e, and this is more readily considered through the application of the RESAF. Whilst some choices (i.e. introducing more insulation and adopting triple-glazed [PVC or aluminium] windows) [reduce or increase] the embodied

carbon of the building itself (1%), this is far outweighed by the annual savings they bring (Table 5-9), which leads to a considerable multiplying effect (between 50 and 100 times) over the building's lifetime. Proposed alternatives considered their resilience within three reported future scenario archetypes: the new sustainability paradigm, policy reform and market forces. This urban futures methodological approach helps evaluate whether the proposed solutions can be implemented and whether they will function and cope with changes in the future. For the base case study in Dammam City, alternative 4 could be considered suitable, saving on long-term cooling and heating demands (30%) and on the materials' embodied carbon (21.60%) and embodied energy (11.34%) because it uses aluminium instead of PVC window frames (please see Section 5.2.5.3 when the NC 3 [absence of other environmental considerations] was discussed);

- Consultations with experts in Saudi Arabia verified the need for such a framework, and the designed framework received favourable feedback and some minor suggestions for improvement, which were addressed. The RESAF outcomes are in line with past studies and hence conformity to user expectations has been achieved;
- The revised RESAF and its user manual were finalised based on the previous point; and
- The user manual gives a brief background about the RESAF, as well as ideas for how to implement the framework with solution examples for the proposed designs (see Appendices E and F). Both the beta and final versions are attached.

6.3. Value of the study

This research study adds value to the field as follows:

- This review research has shown that whilst numerous frameworks exist for implementing resilience and sustainability, they have not been applied in or may not be applicable for adoption in Saudi Arabia. This is because of the special nature of the buildings, the cultural and climatic conditions, ineffective management, poor implementation and an overall lack of public awareness, among other reasons, has resulted in the failure to provide assessment frameworks for construction materials that readily assess, sustainability and resilience in combination (rather than isolation) and cater for the rapidly growing residential building sector in Saudi Arabia, taking into account its local context and conditions;

- Use of the RESAF, an Excel-based application that can be used to quantify the use of building materials for assessment, leads to reduced energy consumption (embodied and long-term use) and carbon emissions. Associated tools are expected to play a critical role in engendering greater use of environmentally sustainable, resilient building materials in Saudi Arabia;
- Practically, the RESAF as a tool targets practitioners (e.g. designers, engineers, contractors) in Saudi Arabia. The tool is currently not available in the country, as it delivers building material selections in early design steps by considering:
    - Adoption of straightforward calculations,
    - Allowing data that can be updated as information changes,
    - Including a wide range of materials,
    - Consideration of both embodied and long-term energy use for materials,
    - Adoption of a two-filter system that combines a sustainability filter and resilience filter in one assessment framework;
- The level of sustainability that can be achieved (i.e. moving toward one planet living and avoiding overshoot days - overshoot occurs when humanity's demand on nature continues to exceed what the Earth's ecosystems can renew) needs to evolve, not least for the construction industry. The RESAF is flexible enough to allow this to happen where further performance questions are raised and knowledge gaps arise necessitating additional research …so the framework can be enhanced, corrected and evolved; and
- The RESAF’s advantages favour the community, as it targets the domestic sector (housing). In reality, fruitful implementation will positively affect almost everybody in the country. This is very much in line with *Saudi Vision 2030*, which favours a much improved sustainability approach.

6.4. Limitations of the research study

The scope of the RESAF was outlined with specific details (see Figure 3-2, Table 4-1 and Figure 4-1 for the RESAF's exact scope). Limitations of the research study are as follows:

- A simplified LCA assessment was used, and a common way of simplifying LCA methodologies is to decrease the number of indicators used or the number of building lifecycle phases included (Oregi et al., 2015). To aid interpretation of the results, the impact categories and indicators should be kept simple. For example, few people would understand the result if eutrophication were an impact category, but they would understand results given in terms of carbon kgCO_2e and embodied energy kWh, as they are widely used and well known (Bribián et al., 2009). That said, as understanding and knowledge of users improves, so can the sophistication of the assessment tools used for domestic properties. One only has to look at how they evolved over the last 30 years to envision what they might look like in the future;
- The scope of the RESAF was outlined with specific details (see Figure 3-2, Table 4-1 and Figure 4-1 for the RESAF's exact scope). There are limitations in the environmental sustainability scope, in other words the RESAF had a narrow focus on the following :
    - Construction material selection for a 'cradle-to-gate';
    - Transport selection from gate-to-grave;
    - U-value calculations for buildings (cooling and heating demand); and
    - Targeting domestic buildings (housing sector).

In part this is to do with the previous point raised – when a tool becomes overly complex it is unlikely to be adopted.

- During building operation, the RESAF focuses on what is important to the user: cooling and heating loads. This is because within Saudi Arabia, cooling systems currently account for around 66% of household electrical demands in summer months (Krarti and Howarth, 2020). Therefore, it is not surprising that domestic buildings consume approximately 43% of the electricity production in the country (General Authority for Statistics, 2018a). Other building operation categories (i.e., lighting and home equipment) could be covered in further works;

- The case study used is a real proposed design (all required information where available). A RESAF user is presumed to utilise the framework even if some of the information is not available. In such cases, appropriate assumptions should be made and suitable justification provided. Note that the accuracy of the results is highly dependent on the availability of information required (highlighted previously in Figure 4-7), as well as the choices made by the users while implementing the framework. This is where experience with using the tool and proper training on how to use it would help;
- Conditions for the future resilience of material choices have been tested using three highly differing scenarios: MF, PR and NSP. However, it should be noted that Hunt et al. (2012) have identified other archetypal scenarios (e.g. fortress world – FW) which were not considered. Adoption of alternative scenarios might be considered …not least as adopting additional scenarios allows further questions to be asked about the resilience of materials adopted. This is the whole point about the resilience filter. That said the scenarios adopted herein reflect well the main archetypal visions of the future; and
- The RESAF is designed to target only those users who are building practitioners (e.g., architects, designers, builders, engineers, contractors) or those interested in the building field (perhaps research bodies, for example).

6.5. Recommendations and further work for this study

It is hoped that in Saudi Arabia sustainability and resilience can be integrated to the maximum extent at the earliest stage possible within the decision-making process. The RESAF presented in the PhD study will help building construction and design projects create a more favourable long-term legacy at each stage of the material selection process. Nevertheless, this framework is a possible pathway to establishing regulations and rules for sustainable and resilient domestic buildings in the country. A number of recommendations are to be forwarded to related stakeholders or further works to be carried out:

- Transforming the RESAF into an online web or mobile application is a possible solution for better implementation in the future. This idea may help to promote the RESAF across the construction industry, as well as enhance how the selection of construction materials is beneficial to sustainability and resilience. For example if the RESAF were launched online and users have applied the framework, by the time it receives user feedback or discussion (presuming a user forum is part of the launch), the users themselves will help upgrade RESAF – in which case allowing RESAF to remain open-source could be a sensible way forward;
- Extending the RESAF scope could be done, which will require further study:
    - More categories in the building and construction material lifecycle, such as construction works or building operation (i.e., lighting and home equipment), should be included;
    - Water embodied for materials and in-use to be included;
    - Including other type of buildings, such as commercial or government buildings;
    - An optimal choice might be found to deliver an appropriate U-value for building elements with minimal embodied carbon (from material choice to long-term in-use performance) and at the lowest possible cost; and
    - The current typical house size can be reduced by studying the architectural principles of house design (i.e., room areas and functions).
- A customised, new version of the RESAF that targets non-expert users (potential house owners) is a further development to the framework. It is expected to require a separate study aimed at house owners. This will increase people's awareness;
- Establishing projects aimed at developing localised databases for Saudi Arabia. These would help provide strong recommendations for construction materials and their embodied carbon, embodied energy and thermal conductivity. These databases would need to be in an accessible 'open-access' formats for ease of access and use by stakeholders. Industry business cooperation is key here not least as information sharing would be required between a range of bodies in order

to produce a database. Making these data available to researchers in the construction community will have a huge impact on environmental studies in Saudi Arabia;

- Government policy is required to encourage the use of sustainable materials. Governance is important as someone needs to own and push the agenda for appropriate material selection. As of yet, no such policy exists for encouraging the engineering community to take steps towards sustainable building material solutions. Regulations that meet sustainable environmental standards must be developed for future implementations, such as setting a maximum amount of embodied carbon or energy for each respective material – with a philosophy of moving towards one planet principles;
- For researchers, resilient domestic buildings is a topic of study still lacking in Saudi Arabia. It is recommended to look at conditions that are more necessary as the world changes and mitigates for (and adapts to) a changing climate. Development of studies on this topic is a promising future endeavour; and
- The construction industry as a whole becoming more environmentally conscious of sustainable building materials in the push for more sustainable business models. However, the construction community and related bodies in Saudi Arabia are only recently becoming aware of sustainability and resilience topics when developing a future vision for the country. This slow uptake may have been because of the special nature of buildings, cultural and climatic conditions, ineffective management, poor implementation and an overall lack of public awareness, among other reasons, and it has resulted in the failure of the available frameworks to cater to the rapidly growing residential building sector in Saudi Arabia. The initiative by the construction community is the drive to establish similar projects to RESAF, and the community facilitators (i.e., ideas and motivations) that are starting to emerge will definitely make a huge difference.

6.6. Summary

This chapter has presented conclusions of the research, from a summary of the study to recommendations for future research. The RESAF is a primary tool adding value to this research study and a major contributing part of bridging the knowledge gap. This research study describes the importance of creating a specific framework for the unique context and local conditions of Saudi Arabia. It illustrates how to select construction materials to reduce carbon emissions and energy usage for both materials (embodied impacts) and the long-term cooling and heating of domestic buildings. In line with this, the following question was asked: are the solutions (selected materials) fit-for -purpose in the future? The answer is it depends how the future unfolds …by better considering resilience through the RESAF approach, buildings in Saudi Arabia can be better equipped for such eventualities.

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Appendix A. List of publications

Almulhim, M. S., Hunt, D. V. and Rogers, C. D. (2018) 'A Framework for Assessing the Environmentally Sustainable and Resilience Performance of Domestic Building Materials in Saudi Arabia'. *Conference Proceedings of the 2nd International Conference on Sustainability, Human Geography and Environment 2018*, Kraków, Poland, 28 November - 2 December 2018, pp. 209 - 214. Available at: https://www.researchgate.net/publication/329505135_A_Framework_for_Assessing_the_Environmentally_Sustainable_and_Resilience_Performance_of_Domestic_Building_Materials_in_Saudi_Arabia (Accessed: 29 August 2020).

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Appendix B. Interview outline and questions

Interview outline and questions

The interview process will be conducted in four steps. All steps descriptions are in Table below, the researcher will indicate (×) in the box once the step has been completed.

Note: During all steps, the participant will have the option to ask questions about the participant information sheet, the consent form, the framework, the interview or any point with respect to the project. The researcher will answer them accordingly and address any concerns raised.

<table>
<tr><th>Steps</th><th>Completed</th></tr>
<tr><td><u>Step 1 (10 minutes):</u>
The participant will be given opportunity to read the participant information sheet and sign the consent form.</td><td></td></tr>
<tr><td><u>Step 2 (10 minutes):</u>
The student researcher (Mohammad Almulhim) will present the beta version of the RESAF and will explain how it works in terms of applying the framework and the outcome.</td><td></td></tr>
<tr><td><u>Step 3 (15 minutes):</u>
The participant will have the chance to read the user’s manual and use the beta version of the RESAF. The purpose of step 3 is to get familiar with the framework and how to use it, as well as to discover the likely inputs required and deliverable outputs.</td><td></td></tr>
<tr><td><u>Step 4 (25 Minutes):</u>
Based on Steps 2 and 3, the participant will provide feedback about the proposed framework, which will include points such as:
Feedback on the project,
Feedback on the framework, including areas for improvement;
Is it easy to use, is there missing information, are the accuracy of the data sufficient for Saudi Arabia, are the outputs appropriate and sufficient, is the RESAF applicable to the Saudi Arabian context and its local conditions.</td><td></td></tr>
</table>

Once Steps 1, 2 and 3 have been conducted, the participant will fill the following two sections:

Section 1: General questions for an overview about the project.

1.1 How would you define sustainability?

1.2 How would you define resilience?

1.3 Are there links between sustainability and resilience?

- ☐ Yes
- ☐ No
- ☐ I do not know
- ☐ I do not want to say

If your answer is [Yes or No], Please explain?

1.4 Do you use any sustainability or resilience assessment tools?

- ☐ Yes
- ☐ No
- ☐ I do not know
- ☐ I do not want to say

You have an option to give more information about assessments and how do you use them.

1.5 How important do you grade each following statement:

Note: consider each statement independently.

	Most important	Important	Slightly Important	Not important	I do not know
Implementing **sustainability** concepts in Saudi Arabian residential buildings.	☐	☐	☐	☐	☐
Implementing **resilience** concepts in Saudi Arabian residential buildings.	☐	☐	☐	☐	☐
Implementing both **sustainability and resilience** concepts in Saudi Arabian residential buildings.	☐	☐	☐	☐	☐
The selection of structural materials will contribute to **sustainability**.	☐	☐	☐	☐	☐
The selection of structural materials will contribute to **resilience**.	☐	☐	☐	☐	☐
The selection of structural materials will contribute to both **sustainability and resilience**.	☐	☐	☐	☐	☐
Saudi Arabia establishing their own assessment for **sustainability**.	☐	☐	☐	☐	☐
Saudi Arabia establishing their own assessment for **resilience**.	☐	☐	☐	☐	☐
Saudi Arabia establishing their own assessment for both **sustainability and resilience**.	☐	☐	☐	☐	☐

You have an option to justify your selection or comment about the statements.

1.6 Saudi Arabia needs to customise assessment procedures for sustainability and resilience due their own context and local conditions.

- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

Would you explain why you selected your answer? Please also give examples of the Saudi Arabian context and local conditions, if you select [Strongly Agree or Agree].

1.7 There are barriers to establishing sustainability and resilience in Saudi Arabia residential buildings.

- Strongly Agree
- Agree
- Neutral
- Disagree
- Strongly Disagree

Would you explain why you selected your answer (Examples of barriers, solutions or inducements)?

Section 2: RESAF feedback

2.1 Grade your agreement with each following statement about the Resilience and Environmentally Sustainable Assessment Framework RESAF for structural materials in domestic buildings (beta version application):

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
The user's manual is considered easy to comprehend and follow.	☐	☐	☐	☐	☐
As 'user', I clearly understand how to use the RESAF confidently.	☐	☐	☐	☐	☐
The RESAF front-page **(input part)** in general, is well presented and clear.	☐	☐	☐	☐	☐
It was easy to fill and select all the forms in the RESAF front-page ***(input / embodied part)***.	☐	☐	☐	☐	☐
It was easy to fill and select all the forms in the RESAF front-page ***(input part / U-value part and annual consumption (energy demand) for cooling or heating load)***.	☐	☐	☐	☐	☐
It was easy to fill and select all the forms in the RESAF front-page (**input part / resilience**).	☐	☐	☐	☐	☐
The front-page **(output part / tables result)** is well presented and clear.	☐	☐	☐	☐	☐
The front-page **(output part – figures result)** is well presented and clear.	☐	☐	☐	☐	☐
It was helpful that the user can get access to (and edit / amend) the database and references list in the background-page.	☐	☐	☐	☐	☐
Based on your experience the result provides an accurate representation (in general).	☐	☐	☐	☐	☐
Based on your experience the **(embodied carbon)** result provides an accurate representation (in general)	☐	☐	☐	☐	☐

Based on your experience the **(embodied energy)** result provides an accurate representation (in general)	☐	☐	☐	☐	☐
Based on your experience the **(U-value and annual consumption "energy demand" for cooling or heating load)** result provides an accurate representation (in general)	☐	☐	☐	☐	☐
Based on your experience the **(cost)** result provides an accurate representation (in general)	☐	☐	☐	☐	☐
Based on your experience the **(resilience)** result provides an accurate representation (in general)	☐	☐	☐	☐	☐

You have an option to justify your selection especially if your selection was [Disagree or Strongly Disagree]?

2.2 By using the framework, are there any missing information **(please consider the database, input filling or results)?**

- Yes
- No
- I do not know
- I do not want to say

Please give details of the missing information if you answer [yes]?

2.3 Database for 'embodied carbon', 'embodied energy' and 'thermal conductivity' were extracted from references not considering Saudi Arabia directly. Do you have or know of any suggested references that consider Saudi Arabia more directly?

- Yes
- No
- I do not know
- I do not want to say

Please list the references if you answer [Yes]?

2.4 Would you use the framework proposed in your work?

- □ Yes
- □ No
- □ I do not know
- □ I do not want to say

Would you explain why you select [Yes or No]? Here, you may write about the benefits or concerns.

Thank you for your time and participation

Appendix C. Participants' response scripts

Table 1 Participants' responses to the descriptive equations in the interview (Section 1: Feedback on the project (a))

Participants (No)	Questions						
	1.1 How would you define sustainability?	**1.2 How would you define resilience?**	**1.3 Are there links between sustainability and resilience?**	**1.4 Do you use any sustainability or resilience assessment tools?**	**1.5 You have an option to justify your selection or comment about the statements?**	**1.6 Saudi Arabia needs to customise assessment procedures for sustainability and resilience due their own context and local conditions. Would you explain why you selected your answer? Please also give examples of the Saudi Arabian context and local conditions**	**1.7 There are barriers to establishing sustainability and resilience in Saudi Arabia residential buildings. Would you explain why you selected your answer (Examples of barriers, solutions or inducements)?**
1	Protecting natural materials that are used in the construction process from depletion or scarcity.	. From an architectural point of view, the ability to use the rooms or spaces in a building in more than activity (in short, design	From the architectural point of view, the link between sustainability and resilience is the possibility of designing buildings with recycled materials	N/A	N/A	1-The climate in Saudi Arabia is very harsh (i.e., hot weather). 2- Materials are abnormally wasted due to the severe neglect of supervision during building	When codes [are] revised, companies keep pace with this modification and development. There are people [who] do not know about the Saudi codes, and they are working [in] the construction industry.

		rooms or spaces with multiple functions). In addition, materials can be recycled to be used more than once.	using buildings for multiple purposes.			construction as well as ignoring maintenance during the building's long-term life. This leads to financial losses in projects that cost billions of dollars.	
2	1- A sustainable building is made up of features that extend the life of the building and its long-term functional use. For example, in design we could: 2- Use rooms that could be adaptable and changed in the future. 3- When designing structural elements (e.g., steel reinforcement in the concrete), no	It is the ability to use the rooms in the building for more functions (i.e., the purpose of a room could be changed). Nowadays, the way of designing houses has changed, such as the house is private and just used by residents, and visitors are hosted in a reception room (Dewaniya) attached to the house.		There is perusal and knowledge of sustainability applications such as solar energy, using alternative materials (e.g., marbles and stones) and expanding the building life span.	Structure materials are important in terms of sustainability; on the other hand, they are less important in resilience as they are stability.	Theoretically, it is not easy to customise tools in the country. For example, the issues with codes [are that they] do not have smart side or building technology.	In construction, the supervision conducted by a structural engineer is not the preferred approach (which is the case in Saudi Arabia). Instead, an architect who has knowledge of architectural solutions and material selection must conduct the supervision. A problem is that people who work in building engineering are not good enough at implementing sustainability.

	additional steel should be added (over-design), so the design does not waste additional materials. 4- As for owners of large homes (higher floor area), when their children become independent, then move to their own houses, owners may want to sell the house but there is no buyer because of the large building that the buyer cannot afford. 5- We try hard to implement sustainability, such as selecting the location of the building and selecting alternatives for						

	materials. 6- Customers' (i.e., home owners') awareness of sustainability is increasing 7- Mostadam assessment is more about considering construction supervision and quality. In any case, it is a beginning that is thought will be developed over time.						
3	Providing a sustainable environment means including natural materials without causing harm to our future generations.	Availability of alternatives without having a negative impact.	The link between resilience and sustainability can exist by providing alternatives that serve sustainability.	There are points within the LEED assessment that make it difficult to apply to assessing sustainability in Saudi Arabia. Therefore, the solution is to establish Saudi Arabian codes to deal with the sustainability assessment procedure.	N/A	The Ministry of Housing has established a sustainable building program (Mostadam), which will be implemented soon. There is a development approach by the ministry linked with Saudi Arabian Vision 2030.	1-The lack of specialists in sustainability and resilience fields. 2-Exploitation of construction contractors and materials suppliers by raising the prices of sustainable materials to unacceptable levels. 3-The lack of sustainability awareness or sustainable culture in the community. 4-My design office [does] not have a copy of the codes, all [that] I have [are]

							drafts.
4	Balance among three aspects: social, economic and environmental.	The ability to adapt and change	Linear relationship	Key performance indicators	N/A	The Saudi Arabian context included several conditions. Therefore, to achieve sustainability, local conditions must be taken into consideration (see next question for these conditions).	The most important current challenge is not having local expertise in the sustainability and resilience fields, as well as the higher prices of sustainable materials.
5	Use local materials in the design in efficient ways, so we can save our natural resources, reduce waste and recycle materials.	Having buildings resistant to earthquakes and our harsh environment. Something we stand our environment.	Most of the time, if we add good resistance to our environment, we will have sustainability.	EPD and LCA form gulf for materials (mix design).		We have a severely harsh environment (High temperature & high humidity). Local material	Not everyone knows about resilience and sustainability concepts. However, there is a trend toward these concepts because of the Saudi Arabian Vision 2030 and membership in the G20 forum.
6	It is to preserve the natural resources in the environment without causing harm to these resources.	Using things without harm or overuse.	Flexibility in choosing materials and objects.	LEED and GSAS.	All building materials must be discussed rather than focus on structural materials.	Reduce CO_2.	Community awareness (culture), in addition to the lack of specialists and those who are interested in the sustainability and resilience concepts. Finally, government financial support for electricity must be reduced (thankfully was this done around 2 years

							ago).
7	Selflessly thinking of the future generations in terms of their wealth and natural resources	The ability to resist changes (with flexibility), as well as the ability to return to the normal state after these changes.	Resilience is [a] path to sustainability, it is [not] possible to withstand the natural situation without sustainable applications…for [example,] dams as sustainable solutions that preserve vegetation and generate alternative energy.	LEED, BREAM, and WELL	N/A	Saudi Arabia needs to build its own framework due to its culture and topography.	[Actually], the endeavours are still in [their infancy]. The country just witnessed last [month] establishing the first [green] building rating system, dedicated [to the] residential sector [in] Mostadam. This [is] also the same for the Saudi green building code issued recently by [the] Ministry of Municipal and Rural Affairs (MOMRA).
8	Presently, all development works are caused out without considering their adverse effects on nature. Minimising the damage caused by reckless decision-making allows future generations to benefit equally from natural-resource development works and	It is the capacity / potential to regain/restore the working system at the earliest back to its natural stage/cause	During [the decision-making] process of sustainability it is advisable that any strategy should have the potential to recover itself from any impact that may alter its original draw/process.	N/A	Considering that [the] development [process] requires both sustainability and [resilience], Saudi Arabia needs to establish tools to measure [the] impact of [decisions] which will have [an] impact on the large construction work in the kingdom.	Saudi Arabia has different climate and geographical conditions (very hot during summer and most the country has desert condition). Considering these two important factor, Saudi Arabia needs to customise assessment procedures.	N/A

	economic solutions.						
9	Using the current available resources without affecting the rights of other people. The problem is excessive consumption. Human greed must be controlled.	The participant preferred to mention an example: when people lived caves, they did not develop buildings for quite a long time. The reason for living in a cave was protection from erosion and avoiding wild and dangerous animals. Development is controlled by the environment, technology and available materials.	Sustainability is rigid [and] follows certain points 1, 2, and 3 etc., [but] resilience [gives] more space so you can move vertically and horizontally.	I do not use any tools, as they do not have clear characteristics for assessment.	The Question: What is the application? The idea of carrots and sticks applied to the community (client) might work to promote sustainability and resilience.	We use traditional construction materials because of the cost. The changes of these materials must be gradual.	There is no supervision during the construction process for buildings, so engineers will overdesign buildings (e.g., use additional steel reinforcement in concrete structures) to protect himself or herself from future issues that might occur because of poor construction.
10	Reaching goals by optimizing the current use of natural resources through a balance between social, environmental and economic aspects, without negatively	The ability to adapt, reuse or re-respond to the surrounding changes or circumstances	My point of view is that a harmonic or liner relationship exists between resilience and sustainability. Resilience helps to achieve sustainability by maintaining goals	N/A	I [think] that resilience should be under the sustainability, as sustainability takes a [long] time to be supported by international bodies. Now	We have to reach the goal and the essence, without quoting the ideas of others outside of our context (e.g., sustainability or resilience tools from other	Lack of community awareness of sustainability and resilience subjects. Lack of experts and professionalism compared to other countries when it comes to sustainability and resilience.

	affecting the future generations.		and optimal utilization of resources over time because variables differ from time to time.		[adding] a new term resilience may not help, so it [is] better [for] resilience to be part of sustainability.	countries), taking into account that the context is important, but the essence is the most vital.	
11	Sustainability (green architecture) is a method of living, which meets the needs of the present generations, reducing harm to the environment, reducing energy consumption, relying on renewable resources and optimizing the use of natural resources to ensure the rights of future generations.	Resilience, in general, is the ability to adapt and change. For example, the ability of the structural elements (i.e., concrete or steel) of buildings to withstand and return to their original states (dimensions) after the release of loads affecting these structural elements.	Achieving resilience in structural materials is one of the reasons why a building is sustainable and thus the relationship is liner.	N/A	150 sustainable government buildings have been established in Saudi Arabia. This is evidence of the government's interest in making the buildings sustainable or the trend toward carefully use of natural materials. In addition, the Saudi Green Building Forum has raised the interest in sustainability.	Sustainability and its advantages when are important to implement. Advantages include reducing energy consumption and pollution, which will positively affect human health and minimise the harm to the planet	I disagree because Saudi Arabia [has] actually [started] to construct sustainable government buildings, [which is evidence] that Saudi Arabia [has] the ability to implement it in all buildings, we just [need] more time and awareness of the importance of sustainability and resilience.

12	The ability to preserve the quality of life we currently have for the long term, which in turn depends on the conservation of our world and the responsible use of natural resources	A measure of the response of a value to a relative change in another value, or the response of one factor to changes in another factor. The ability of objects to affect their shape and size after the cause of the change is removed or released.	Sustainability represents resilience over time.	N/A	N/A	N/A	Sustainability material prices are higher compared to other materials.
13	As a consultant, we express sustainability as "structures that are environmentally friendly and able to use all resources (preferably natural resources) efficiently, starting from the design stage through its lifetime until demolition".	Resilience is the ability of a structure to weather any extreme event that occurs, minimise damage and functional disruption to the structure, facilitate rapid repairs without interrupting its function, and recover quickly to its original intended function	N/A	N/A	Much more research needs to be done in KSA on local construction materials, considering the local harsh desert environment, including but not limited to extremely high temperatures, 100% humidity in coastal regions, salt-laden atmosphere, etc., to design and construct resilient	N/A	Inadequate/inexperienced local work force in the technical field is encountered, and they need to be trained extensively.

					structures.		
14	The application of knowledge, experience, skills …. to a current or proposed project to optimise best practices in order to satisfy main dimensions of economic , social and environment for safer generations.	The flexibility of the system to cooperate or fit with different scenarios	A direct relationship exists between resilience and sustainability	LEED / BREEAM has been used to check the sustainability of my project during MSc study	N/A	Government policy should be facilitated Lack of public awareness Guidelines and specifications	Government policy should be facilitated Lack of public awareness Guidelines and specifications
15	To me sustainability focuses on the balance and harmony between the 3 P's, people, profit, and planet. Sustainability is nothing without the achievement of all the aspects of the 3 P's.	It's the ability to withstand changes of any natural situation at hand. Resiliency in environment for example meaning the ability to mitigate and adapt to climate shifts and climate changes.	The ability to adapt to the changing triple bottom line of sustainability is crucial today. If one pillar of sustainability is compromised or neglected then that is the opposite meaning of resiliency.	I refer to several sustainability assessment tools such as LEED, estidama, and the building challenge standard. For resiliency, I refer to GRESB.	Having a sustainability and resilient era in Saudi is very important, but I believe having a special Saudi sustainability and resiliency assessment system is not as important because we can use international tools that are flexible enough to be modified to our needs.	We have a unique era and cultural conditions that need to be addressed and respected. Therefore, if we use international systems that measure sustainability or resiliency, then they must be able to adapt our unique behavioural and cultural aspects, such as achieving privacy and a modern style.	Such barriers include a lack of knowledge of the importance to the end user. In addition, we have a lack of government support or an incentive system to full sustainability. We have new [codes] and regulations but we still lack acceptance and man power to help put these codes [into] actual practice. We also have [a lack] of public acceptance [of] new systems and codes which we can call resistance. * Sustainability accounted for maybe 10% of the Mostadam assessment.

16	When we use things, we use them in a way that also enables future generations to use them.	N/A	N/A	LCA / Simapro			Stakeholders do not share information with researchers.
17	*'The ability of the present generation to meet their needs without endangering or compromising the ability of future generations to meet their own needs' (Brundtland ,1987)*	It is the ability of adaption and meeting the needed function, in light of the risks and potential challenges.	Greater resiliency will lead to greater sustainability, because it delivers function without using created or new resources.	LEED certification for neighbourhood development	N/A	The Western world is different compared to Saudi Arabia because of several reasons: Local construction techniques, resource abundance, construction regulations and legislation.	Lack of awareness or understanding of benefits of sustainability by the majority of society. There is a shortage of investment in sustainability projects by investors. There are also no government incentives for sustainable residential building projects.
18	The ability of current generations to meet their needs, without compromising the ability of future generations to meet their own needs.	Meeting current needs while adapting to external influences or factors.	Resilience is an influential reason to raise the level of sustainability.	N/A	N/A	To reduce the level of carbon emissions and improve the health of the environment	1- There is a lack of understanding about the ongoing issues concerning the environment in Saudi Arabia. 2- Few studies exist that address environmental issues. 3- Environmental challenges are increasing.

19	The ability to maintain the kind of life humans can enjoy for a long time	The ability of a given system to adapt and respond to specific challenges before society's ability to anticipate the challenges it may face.	Resilience is part of sustainability, as it keeps a building durable.	Implementing a program for environmentally friendly concrete factories	N/A	Lack of cooperation from private sector companies regarding environmental information (e.g., related to products including construction materials).	High prices of sustainable and resilient materials
20	Sustainability is an environmental term that means conserving natural resources and saving energy	The ability to adapt to expected and unexpected circumstances	When a building is resilient, the percentage (in other words, possibility) of reaching sustainability is increased (e.g., natural resources will be saved).	I am currently developing an application (program) for environmentally friendly concrete factories.	N/A	No public transportation is available in the cities; hence, the only available transportation is cars.	The lack of sustainability and resilience culture in the community The authorities delayed implementing standards and enforcing them on individuals.
21	It measures the environmental, economic and social aspects and ensures the efficient use of materials and reduced consumption of energy and water.	Durability and the quality of the materials or system	Resilience can lead to sustainability.	N/A	It is believed that resilience is not changeable with the factors linked to Saudi Arabian conditions and contexts, so the assessments or tools do not need to be developed if taken from outside Saudi Arabia. However,	I agree with having customised sustainability assessment methods or tools within Saudi Arabia. However, for resilience, other assessment methods can be implemented in Saudi Arabia with	No barriers to establishing sustainability and resilience exist within the kingdom. Barriers existed in the past but not nowadays.

					for sustainability, we need assessments or tools specifically developed for Saudi Arabia, due to factors such as community awareness, culture differences and hot weather.	no customization because the materials are somehow universal.	
22	Use materials and tools that create benefits for the longest term.	Obtain the maximum benefits of the systems.	For example, designing a building with materials and systems with high resilience to benefit greater long-term life.	Value engineering LEED	N/A	Hot weather and humidity. The desert (we can take advantage of the sand)	Administrative procedures for implementing projects and lack of experience. The solution: the relevant authorities adopt ideas and procedures related to the environment (sustainability and resilience)

Table 2 Participants' responses to the descriptive equations in the interview (Section 2: Feedback on the framework (b))

Participants (No)	Questions			
	2.1 Grade your agreement with each following statement about the Resilience and Sustainability Assessment Framework RSAF for structural materials in domestic buildings (beta version application): You have an option to justify your selection especially if your selection was [Disagree or Strongly Disagree]?	**2.2 By using the framework, are there any missing information (please consider the database, input filling or results)? Please give details of the missing information if you answer [yes]?**	**2.3 Database for 'embodied carbon', 'embodied energy' and 'thermal conductivity' were extracted from references not considering Saudi Arabia directly. Do you have or know of any suggested references that consider Saudi Arabia more directly? Please list the references if you answer [Yes]?**	**2.4 2.4 Would you use the framework proposed in your work? Would you explain why you select [Yes or No]? Here, you may write about the benefits or concerns.**
1	This study will help in many ways in the process of selecting appropriate construction materials in the future because of the flexibility of the framework within this study in choosing the materials (variety of options)	N/A	N/A	Fruitful attempt to develop this framework; we strongly support it in the field of construction. Raising the awareness of those in charge of construction projects is needed, in terms of buildings materials and their negative effects.
2	I have not tried the framework and will rely on a researcher presentation.	N/A	- King Abdulaziz City for Science and Technology (KACST).	Try to help you even in a simple way.

3	References in the User's Guide are important	N/A	N/A	A framework will help in the study of building projects and the design process.
4	N/A	*Information or data about the design stages and alternatives.	N/A	Ease of use and comprehensiveness of the framework.
5	N/A	N/A	For same producers and consultants	It will help save natural resources, save energy, reduce carbon emission, adapt to climate change (Paris Agreement 2015), achieve Saudi Vision 2020 and 2030, and achieve sustainable development.
6	N/A	N/A	- King Abdulaziz City for Science and Technology (KACST). - Presidency of Meteorology and Environment (PME.	To decide on the choice of construction materials at the design stage of the building.
7	N/A	The reason behind creating such [a] framework and its position among other frameworks.	- The Saudi Standards, Metrology, and Quality Organization (SASO). -The Saudi Energy Efficiency Centre (SEEC).	It depends on the case [and] its location and conditions.

8	N/A	N/A	N/A	Any tool that can help understand the selection process of materials and its impact on sustainability is welcome, Awareness of the tools and their implementations will go a long way toward having a system that meets the growing needs of the present population.
9	“Simplify the results to be per m^2”, “This framework is for experts” and “Can the non-expert use it?” I haven't read through the user manual to judge how clear it is.	N/A	Saudi Contractors Authority	The idea of the framework caught my attention
10	N/A	I see this framework as successful and very effective, especially if we consider that architectural or urban design is essential to sustainability and resilient buildings, before starting the construction process.	- King Abdulaziz City for Science and Technology (KACST). - King Abdullah Petroleum Studies and Research Centre.	What was presented is a practical and effective framework. I hope that you will publish it on your site approved by your university so that you can develop it in the future, but I see it as a turning point in the Saudi Arabian market as soon as it is published.

11	N/A	*Explain the alternatives materials (friendly and non-friendly). Add green materials because they benefit the environment as they absorb carbon and reduce heat (i.e. they are used as insulation in some countries).	N/A	To take advantage of the framework that helps create sustainable buildings
12	N/A	N/A	N/A	It is easily used.
13	N/A	N/A	N/A	N/A
14	I would suggest to specify the cost to the operation cost instead.	N/A	I would suggest contacting SASO. However, I am not quite sure they will cooperate due to confidential issues.	It should be mentioned that it is excellent piece of work and wish all the best to the student in his PHD.
15	N/A	Just if a Saudi data input can be added to the framework, which could be organized with SASO and/or individual Saudi companies that supply construction material.	Must coordinate with SASO and the National Energy Services Company (TARSHID)	I think it will provide a strong case to prove how much details [of] the sustainability and resiliency of a building can be in [a] quantitative and referenced platform and not just quantitative and theoretical.

16	The user manual could be improved.	N/A	The participant suggested that some data (not all) might have been developed but not published.	There is not a similar framework
17	N/A	Geographic Information System (GIS) to be included, such as land use and conditions.	N/A	This framework can be used in renewal and issuance of licenses for buildings.
18	N/A	Not including other building effects, for example lighting.	N/A	Reducing the level of carbon by reducing the transportation distance between the factory and the building construction site.
19	N/A	Building a life cycle that is preferably longer than 50 years.	N/A	The proposed framework can be applied to our work in the Concrete Quality Program
20	N/A	No input about constructing stage, although it has a minor effect	N/A	Application of quality standards in studies and buildings projects and approved materials that apply sustainability and resilience
21	Because I am not sure about the result and database.	(1) Unit selection. It is good to have an option of unit selection (metric – imperial). (2) A full report can be generated from the Excel software.	Saudi Electricity Company	As a company, we have large numbers of houses within the community. It will be helpful to the company to use the proposed framework and meet the sustainability and resilience of the company's houses.

22	N/A	Generally	N/A	It helps to choose materials with high sustainability and resilience The engineering department in my company can benefit from this .program

Appendix D. Feedback on the project (a)

The purpose of this interview section is to present the feedback about the project generally and understand the participants' views on the beta version of RESAF.

As an introduction in the interview process, participants were asked to define the terms sustainability and resilience. Most of the participants were able to define these terms in a reasonably correct manner. It is interesting to note that the majority of respondents asked for some clarification about the term resilience, which was expected due to it being considered a new construction term for domestic properties constructed in Saudi Arabia.

Some participants defined these terms in their own ways; see selected definitions in Table 1 and Table 2. For example, participants referred to sustainability as *'a method of living'*, *'balance and harmony between the 3 P's, people, profit, and planet'* or *'the application of knowledge, experience, skills'*. Regarding resilience, they referred to obtaining *'the maximum benefits of the systems'* or *'the ability to mitigate and adapt'*. All of these expressions indicate how participants look at these terms differently.

Table 1 Selected participant definitions for sustainability

Participant No.	Sustainability
11	*'Sustainability (green architecture) is a method of living, which meets the needs of the present generations, reducing harm to the environment, reducing energy consumption, relying on renewable resources and optimizing the use of natural resources to ensure the rights of future generations'.*
15	*'To me sustainability focuses on the balance and harmony between the 3 P's, people, profit, and planet. Sustainability is nothing without the achievement of all the aspects of the 3 P's'.*
14	*'The application of knowledge, experience, skills .... to a current or proposed project to optimise best practices in order to satisfy main dimensions of economic , social and environment for safer generations'.*

Table 2 Selected participant definitions for resilience

Participant No.	Resilience
15	*'It's the ability to withstand changes of any natural situation at hand. Resiliency in environment for example meaning the ability to mitigate and adapt to climate shifts and climate changes'.*
22	*'Obtain the maximum benefits of the systems'.*
17	*'It is the ability of adaption and meeting the needed function, in light of the risks and potential challenges'.*

Figure 1 shows that the majority of the participants suggested that there are links between sustainability and resilience.

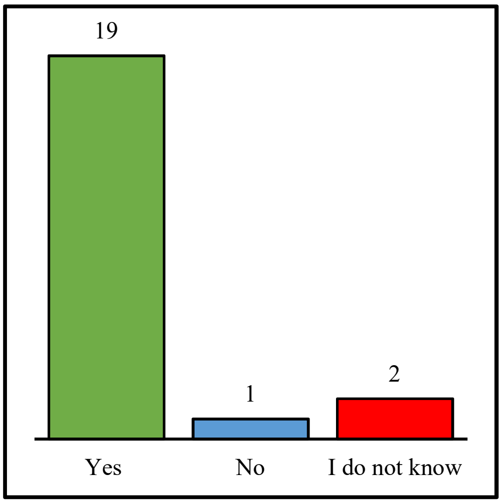

Figure 1 Are there links between sustainability and resilience?

Each participant explained his or her choice. One participant (No. 15) explained the links with the following justification: *'The ability to adapt to the changing triple bottom line of sustainability is crucial today. If one pillar of sustainability is compromised or neglected then that is the opposite meaning of resiliency'.* Another participant (No. 7) suggested that *'resilience is [a] path to sustainability, it is [not] possible to withstand the natural situation without sustainable applications…for [example,] dams'.* Both replies show different views. The first somehow supports the meaning that maintaining sustainability leads to resilience; on the other hand, the second supports the meaning that the purpose of sustainability is to maintain resilience. Generally, both participants have their own arguments, but the most crucial element here is the agreement that sustainability and resilience could work/merge together.

The only participant (No. 9) who said that there are no links suggested that *'sustainability is rigid [and] follows certain points 1, 2, and 3 etc., [but] resilience [gives] more space so you can move vertically and horizontally'*. The participant here does not take into account that sustainability (as a solution) provides a variety of alternatives. If resilience is applied as a solution as well, it will also provide new alternatives which will be ready to use during the decision-making process. There is a supportive example by one participant (No. 8) who agrees that there are links, and the justification was, *'During [the decision-making] process of sustainability it is advisable that any strategy should have the potential to recover itself from any impact that may alter its original draw/process'*. This supports readily the ethos of this research work.

Figure 2 shows that 16 out of 22 participants use sustainability and resilience assessment tools.

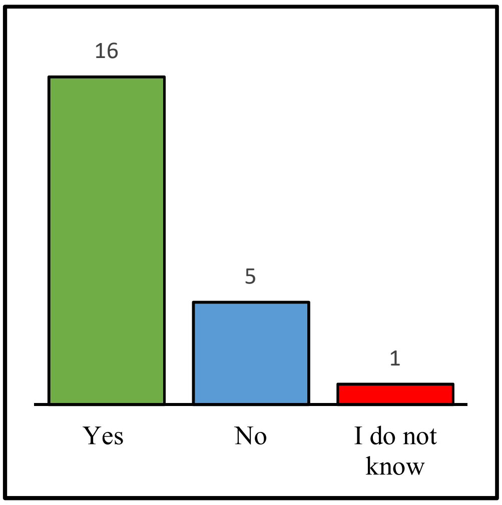

Figure 2 Do you use any sustainability or resilience assessment tools?

These tools can be categorised as follows:

1- Well-known sustainability tools (LEED, BREEAM and LCA, as well as applications such as SimaPro and EPD);
2- Less well-known sustainability tools (Estidama, Building challenge standard and WELL); and
3- Supported tools (key performance indicators [KPIs] and Value engineering).

Notably, two participants (Nos. 19 and 20) are developing an application for environmentally friendly concrete factories. There is also just one participant (No. 15) using a resilience tool, which is Global Real Estate Sustainability Benchmark (GRESB) https://gresb.com/gresb-real-estate-assessment/.

Figure 3 reports the importance rating for nine statements in the context of Saudi Arabian sustainability and resilience. These statements cover residential buildings and structure materials, as well as establishing a unique assessment for Saudi Arabia. Note here that the participants considered each statement independently.

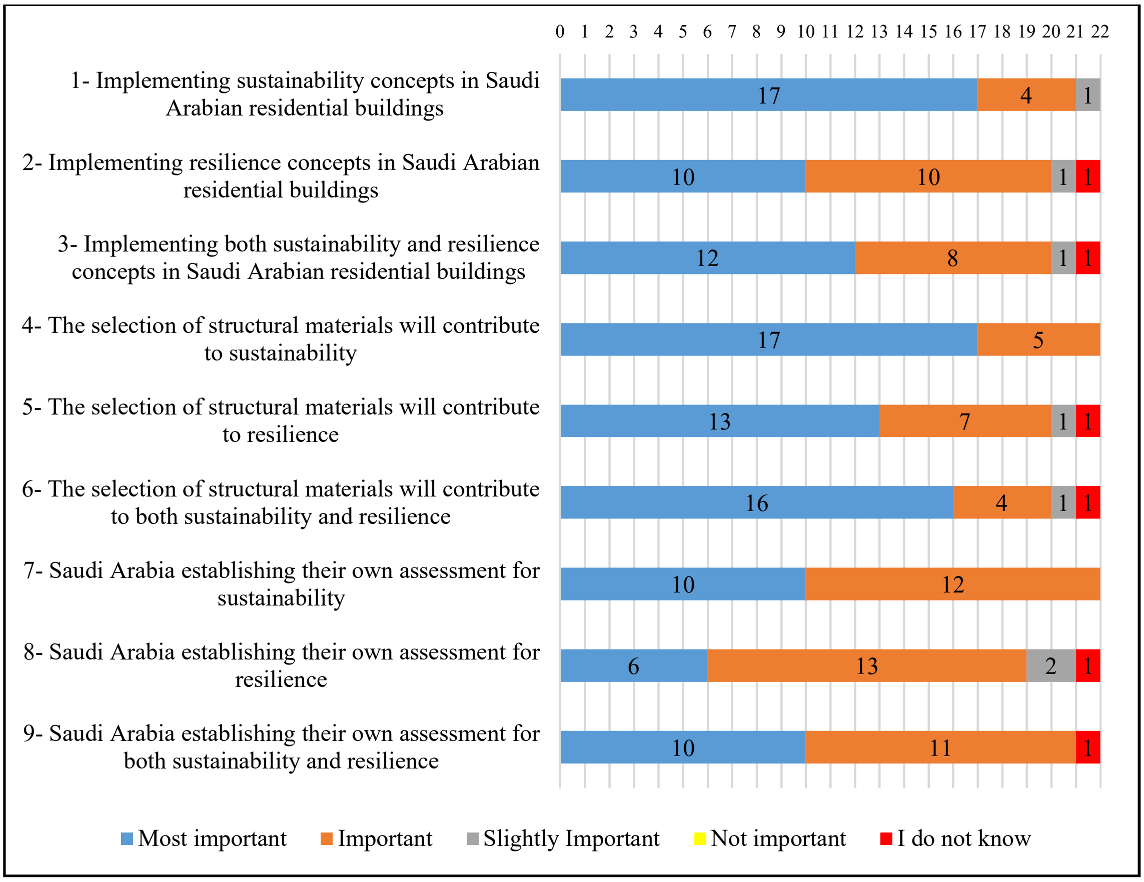

Figure 3 The importance of statements related to sustainability and resilience

The majority of participants rated all the different statements as most important or important. This illustrates the importance of implementing and establishing sustainability and resilience in the country. One participant (No. 8) explained why this is the case: *'Considering that [the] development [process] requires both sustainability and [resilience], Saudi Arabia needs to establish tools to measure [the] impact of [decisions] which will have [an] impact on the large construction work in the kingdom'* ('the kingdom' refers to Saudi Arabia).

Regarding the importance of these statements, one participant (No. 10) said, *'I [think] that resilience should be under the sustainability, as sustainability takes a [long] time to be supported by international bodies. Now [adding] a new term resilience may not help, so it [is] better [for] resilience to be part of sustainability'*. Even though this participant was among the participants who selected most important or important for all statements, the participant provided an opinion about the term/concept of resilience. Although resilience is a new term, that does not mean it is not recognised in our modern day. Discovering the purpose of resilience in any project is the key. For example, in this project (RESAF), resilience emphasises the future-proofing of the sustainable solutions/selected materials.

Figure 4 shows the participants' responses when asked about customising assessment tools due to the context and local conditions of Saudi Arabia: 17 strongly agreed and 4 agreed.

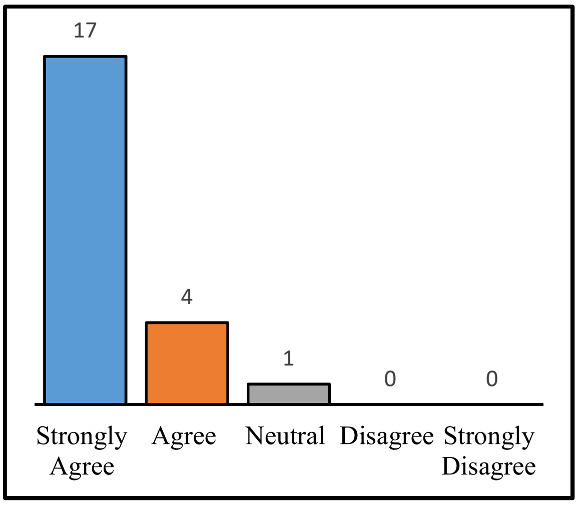

Figure 4 Saudi Arabia needs to customise assessment procedures for sustainability and resilience due its own context and local conditions

Going back to the introduction section (p. 4), factors of Saudi Arabia's different context have been reported in past studies. Participants raised most of them again, as well as the following additional factors:

- Neglect of supervision and maintenance;
- Lack of corporations in the supply sector offering environmental information; and
- Using conventional building materials because of the cost.

Figure 5 shows the participants' responses when asked about whether there are barriers to establishing sustainability and resilience in the country: 11 strongly agreed that there are barriers to overcome, whilst 6 agreed. On the other hand, 3 responded their views were neutral whilst only 2 disagreed and nobody strongly disagreed. In conclusion the majority agree there are barriers still to overcome.

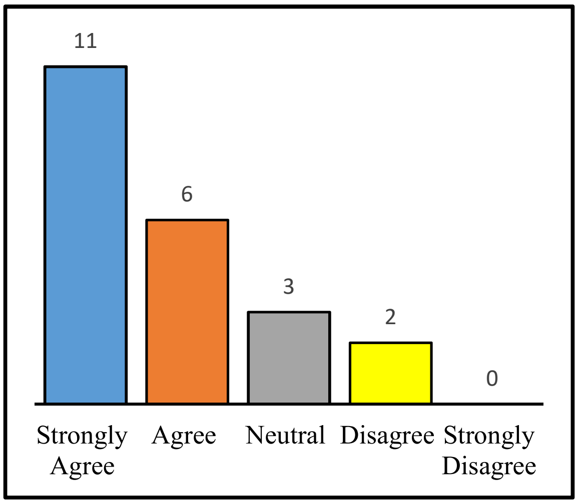

Figure 5 There are barriers to establishing sustainability and resilience in Saudi Arabian residential buildings.

A number of barriers were disclosed, as follows:

- Stakeholders not sharing environmental information with researchers;
- Lack of studies and research centres;
- Expensive cost for sustainable and resilient materials;
- Lack of experienced practitioners as well as lack of knowledge and importance by the end user;
- No government incentives for sustainable homes; and
- Code and regulation issues.

With respect to the participant who was neutral, they still proposed barriers. However, two participants (Nos. 11 and 21) disagreed, the former issuing the following justification: *'I disagree because Saudi Arabia [has] actually [started] to construct sustainable government buildings, [which is evidence] that Saudi Arabia [has] the ability to implement it in all buildings, we just [need] more time and awareness of the importance of sustainability and resilience'*. A reply to this justification is that even though there are sustainable buildings in the country, these efforts are still in the early stages, and more work can and should be done to facilitate the challenges facing sustainability and resilience in the country.

During this stage of interviews, the Saudi building code subject was discussed briefly. See Table 3 for the comments.

Table 3 Comments about Saudi building codes

Participant No.	Comments
15	*'…We have new [codes] and regulations but we still lack acceptance and man power to help put these codes [into] actual practice. We also have [a lack] of public acceptance [of] new systems and codes which we can call resistance'.*
3	*'My design office [does] not have a copy of the codes, all [that] I have [are] drafts'.*
2	*'The issues with codes [are that they] do not have smart side or building technology'*
1	*'When codes [are] revised, companies keep pace with this modification and development. There are people [who] do not know about the Saudi codes, and they are working [in] the construction industry'.*
7	*'[Actually], the endeavours are still in [their infancy]. The country just witnessed last [month] establishing the first [green] building rating system, dedicated [to the] residential sector [in] Mostadam. This [is] also the same for the Saudi green building code issued recently by [the] Ministry of Municipal and Rural Affairs (MOMRA)'.*

It seems that implementing the codes might present challenges, as the construction industry is still learning (Section 2.5.2.2). There is still hope and a light at the end of the tunnel in terms of the codes facilitating a more sustainable outcome. This is because the codes will be implemented in the housing sector in August 2020. Therefore, it is still too soon to evaluate the situation and the experience. However, the comments about the lack of acceptance and putting these codes into actual practice is concerning. Not least with respect to the Mostadam assessment (Section 2.5.2.7), two of the participants (Nos. 2 and 15) suggested that it is merely a process for implementing supervision of the building construction, not a sustainability assessment *per se*. One of them said sustainability accounted for maybe 10% of the assessment. Again, it is too soon to make a clear evaluation of these efforts; more time is needed. All of these efforts give positive signs that changes are happening on the ground. A post-review of these efforts, when they have been officially implemented for a few years is strongly recommended for better criticism based on real life application and practical collated facts as opposed to anecdotal information.

Appendix E. Data tables

Table 1 Embodied carbon and energy of materials after (Hammond and Jones, 2011a).

Categories	Types	Embodied energy (MJ)	Embodied carbon ($kgCO_2e$)
Aggregate and Sand	General Aggregate	0.083	0.0052
	General Sand	0.081	0.0051
	Granite	11	0.7
	Marble tile	3.33	0.21
Aluminium	General Aluminium	155	9.16
	Cast Products	159	9.22
	Extruded	154	9.08
	Rolled	155	9.18
Bitumen	General Bitumen	51	0.405
Block	Concrete block: (8 MPa)	0.59	0.063
	Concrete block: (10 MPa)	0.67	0.078
	Concrete block: (12 MPa)	0.72	0.088
	Concrete block: (13 MPa)	0.83	0.107
	Autoclaved aerated block	3.5	0.32595
	General Clay Bricks	3	0.24
	Limestone bricks	0.85	
Carpet	General Carpet	74	4.134
	Felt (Hair and Jute) Underlay	19	1.0282
	Nylon (Polyamide), pile weight 300 g/m^2	433.33	22.33
	Nylon (Polyamide), pile weight 500 g/m^2	360	19.4
	Nylon (Polyamide), pile weight 700 g/m^2	328.57	18.14
	Nylon (Polyamide), pile weight 900 g/m^2	307.78	17.33
	Nylon (Polyamide), pile weight 1100 g/m^2	297.27	16.73
	Nylon (Polyamide) carpet tiles, pile weight 300 g/m^2	593.33	25.83
	Nylon (Polyamide) carpet tiles, pile weight 500 g/m^2	458	21.4
	Nylon (Polyamide) carpet tiles, pile weight 700 g/m^2	398.57	19.57
	Nylon (Polyamide) carpet tiles, pile weight 900 g/m^2	364.44	18.56
	Nylon (Polyamide) carpet tiles, pile weight 1100 g/m^2	343.64	17.91
	Polyethylterepthalate (PET)	106	5.8936
	Polypropylene	95.4	5.2788
	Polyurethane	72	3.9856
	Rubber	104	5.8777
	Saturated Felt Underlay (impregnated with Asphalt or tar)	32	1.749
	Wool	106	5.8618
Cement	Average CEM I Portland Cement, 94% Clinker	5.5	0.95
	6-20% Fly Ash (CEM II/A-V)	4.895	0.825

	21-35% Fly Ash (CEM II/B-V)	4.065	0.685
	21-35% GGBS (Ground Granulated Blast furnace Slag) (CEM II/B-S)	4.49	0.71
	36-65% GGBS (CEM III/A)	3.585	0.515
	66-80% GGBS (CEM II/B)	2.68	0.32
	Fly Ash	0.1	0.00848
	Slag (GGBS)	1.6	0.08798
	Fibre Cement Panels - Uncoated	10.4	1.1554
	Fibre Cement Panels - (Colour) Coated	15.3	1.3568
	Mortar (1:3 cement:sand mix)	1.33	0.221
	Mortar (1:4)	1.11	0.182
	Mortar (1:5)	0.97	0.156
	Mortar (1:6)	0.85	0.136
	Mortar (1:½:4½ Cement:Lime:Sand mix)	1.34	0.213
	Mortar (1:1:6 Cement:Lime:Sand mix)	1.11	0.174
	Mortar (1:2:9 Cement:Lime:Sand mix)	1.03	0.155
	Cement stabilised soil (5%)	0.68	0.061
	Cement stabilised soil (8%)	0.83	0.084
Ceramics	General Ceramics	10	0.7
	Fittings - Ceramics	20	1.14
	Sanitary Products - Ceramics	29	1.61
	Tiles and Cladding Panels - Ceramics	12	0.78
	General Vinyl Flooring	65.64	3.19
	Vinyl Composite Tiles (VCT)	13.7	
Ready Mix Concrete	RC (25-30 MPa) - 100% Portland cement (CEM I)	0.91	0.14
	RC (25-30 MPa) - 15% Fly Ash	0.85	0.13
	RC (25-30 MPa) - 30% Fly Ash	0.77	0.115
	RC (25-30 MPa) - 25% Blast Furnace Slag	0.78	0.111
	RC (25-30 MPa) - 50% Blast Furnace Slag	0.65	0.081
	RC (28-35 MPa) - 100% Portland cement (CEM I)	0.95	0.148
	RC (28-35 MPa) - 15% fly ash	0.9	0.138
	RC (28-35 MPa) - 30% fly ash	0.82	0.124
	RC (28-35 MPa) - 25% Blast Furnace Slag	0.83	0.119
	RC (28-35 MPa) - 50% Blast Furnace Slag	0.69	0.088
	RC (32-40 MPa) - 100% Portland cement (CEM I)	1.03	0.163
	RC (32-40 MPa) - 15% fly ash	0.97	0.152
	RC (32-40 MPa) - 30% fly ash	0.89	0.136
	RC (32-40 MPa) - 25% Blast Furnace Slag	0.91	0.133
	RC (32-40 MPa) - 50% Blast Furnace Slag	0.78	0.1
	RC (40-50 MPa) - 100% Portland cement (CEM I)	1.17	0.188
	RC (40-50 MPa) - 15% fly ash	1.1	0.174
	RC (40-50 MPa) - 30% fly ash	0.99	0.155
	RC (40-50 MPa) - 25% Blast Furnace Slag	1.03	0.153
	RC (40-50 MPa) - 50% Blast Furnace Slag	0.87	0.115
Precast Concrete	Precast RC (25-30 MPa) - 100% Portland cement (CEM I)	1.36	0.169
	Precast RC (25-30 MPa) - 15% Fly Ash	1.3	0.159

	Precast RC (25-30 MPa) - 30% Fly Ash	1.22	0.144
	Precast RC (25-30 MPa) - 25% Blast Furnace Slag	1.23	0.14
	Precast RC (25-30 MPa) - 50% Blast Furnace Slag	1.1	0.11
	Precast RC (28-35 MPa) - 100% Portland cement (CEM I)	1.4	0.177
	Precast RC (28-35 MPa) - 15% fly ash	1.35	0.167
	Precast RC (28-35 MPa) - 30% fly ash	1.27	0.153
	Precast RC (28-35 MPa) - 25% Blast Furnace Slag	1.28	0.148
	Precast RC (28-35 MPa) - 50% Blast Furnace Slag	1.14	0.117
	Precast RC (32-40 MPa) - 100% Portland cement (CEM I)	1.48	0.192
	Precast RC (32-40 MPa) - 15% fly ash	1.42	0.181
	Precast RC (32-40 MPa) - 30% fly ash	1.34	0.165
	Precast RC (32-40 MPa) - 25% Blast Furnace Slag	1.36	0.162
	Precast RC (32-40 MPa) - 50% Blast Furnace Slag	1.23	0.129
	Precast RC (40-50 MPa) - 100% Portland cement (CEM I)	1.62	0.217
	Precast Precast RC (40-50 MPa) - 15% fly ash	1.55	0.203
	Precast RC (40-50 MPa) - 30% fly ash	1.44	0.184
	Precast RC (40-50 MPa) - 25% Blast Furnace Slag	1.48	0.182
	Precast RC (40-50 MPa) - 50% Blast Furnace Slag	1.32	0.144
Glass	Toughened glass	23.5	1.35
	Primary Glass	15	0.91
	Fibreglass (Glasswool)	28	1.6324
Insulation	General Insulation	45	1.9716
	Cellular Glass	27	
	Cellulose	2.12	
	Cork	4	0.2014
	Fibreglass (Glasswool)	28	1.431
	Flax (Insulation)	39.5	1.802
	Mineral wool	16.6	1.28
	Paper wool	20.2	0.6678
	Polyurethane Flexible Foam	102.1	4.84
	Polyurethane Rigid Foam	101.5	4.26
	General Polyethylene	83.1	2.54
	Expanded Polystyrene	88.6	3.29
	Rockwool	16.8	1.12
	Woodwool (loose)	10.8	
	Woodwool (Board)	20	1.0388
	Recycled Wool	20.9	
Paint	General Paint	70	2.91
	Waterborne Paint	59	2.54
	Solventborne Paint	97	3.76
Paper	Paperboard (General construction purposes)	24.8	1.3674
	Wallpaper	36.4	2.0458
Plaster	General plaster (Gypsum)	1.8	0.13

	Plasterboard	6.75	0.39
Plastics	PVC General	77.2	3.1
	PVC Pipe	67.5	3.23
	Calendered Sheet PVC	68.6	3.19
	PVC Injection Moulding	95.1	3.3
	UPVC Film	69.4	3.16
	General Plastic	80.5	3.31
	(Acrylonitrile butadiene styrene) ABS	95.3	3.76
	General Polyethylene	83.1	2.54
	High Density Polyethylene (HDPE) Resin	76.7	1.93
	HDPE Pipe	84.4	2.52
	Low Density Polyethylene (LDPE) Resin	78.1	2.08
	LDPE Film	89.3	2.6
	Nylon (Polyamide) 6	120.5	9.14
	Nylon (Polyamide) 6,6	138.6	7.92
	Polycarbonate	112.9	7.62
	Polypropylene, Orientated Film	99.2	3.43
	Polypropylene, Injection Moulding	115.1	4.49
	Expanded Polystyrene	88.6	3.29
	General Purpose Polystyrene	86.4	3.43
	High Impact Polystyrene	87.4	3.42
	Thermoformed Expanded Polystyrene	109.2	4.39
	Polyurethane Flexible Foam	102.1	4.84
	Polyurethane Rigid Foam	101.5	4.26
Soil	General (Rammed) Soil	0.45	0.024
	Cement stabilised soil (5%)	0.68	0.061
	Cement stabilised soil (8%)	0.83	0.084
	GGBS stabilised soil	0.65	0.047
	Fly ash stabilised soil	0.56	0.041
Steel	Steel: Section / Primary (100% hypothetical virgin)	38	3.03
	Steel: Section / World Typical - World %39 recycle	27.1	2.03
	Steel: Section / R.O.W. Typical - %35.5 recycle	28.1	2.12
	Steel: Section / UK Typical - EU %59 recycle	21.5	1.53
	Reinforcement steel - ready mix concrete	25.17	1.86
	Reinforcement steel - precast	36.3	4.36
Timber	Glue laminated timber	12	0.87
	Timber: Laminated veneer lumber	9.5	0.65
	Timber: Swan hardwood	10.4	0.87
	Timber: Swan softwood	7.4	0.59
	Timber: Plywood	15	1.1
	Timber: Particle boards	14.5	0.86
	Timber: Oriented strand board (OSB)	15	0.99

Table 2 Transportation carbon coefficients for different types of activities (Department for Business, Energy & Industrial Strategy, 2018)

Transport mode	Type	ECC_{transp}		
		Freighting goods conversion factors (1)	Well-to-tank (WTT) conversion factors (2)	Total (1) + (2)
		kg CO_2e / tonne.km	kg CO_2e / tonne.km	kgCO_2e / tonne.km
HGV Diesel	Rigid (>3.5 - 7.5 tonnes)	0.48674	0.11592	0.60266
	Rigid (>7.5 tonnes-17 tonnes)	0.3581	0.08518	0.44328
	Rigid (>17 tonnes)	0.17927	0.04268	0.22195
Vans Diesel	Class I - Diesel (up to 1.305 tonnes)	0.63206	0.15092	0.78298
	Class II - Diesel (1.305 to 1.74 tonnes)	0.65111	0.15548	0.80659
	Class III - Diesel (1.74 to 3.5 tonnes)	0.51618	0.12326	0.63944
	Average - Diesel (up to 3.5 tonnes)	0.54441	0.13	0.67441
Vans Petrol	Class I - Diesel (up to 1.305 tonnes)	0.63206	0.15092	0.78298
	Class II - Petrol (1.305 to 1.74 tonnes)	0.95734	0.26086	1.2182
	Class III - Petrol (1.74 to 3.5 tonnes)	0.57148	0.15572	0.7272
	Average - Petrol (up to 3.5 tonnes)	0.8115	0.22112	1.03262
Rail	Freight train	0.033505329	0.00756	0.041065329
Freight flights	Domestic	5.8333	0.63882	6.47212
	Short-haul: International flights (up to 3700 km distance)	1.9469	0.21329	2.16019
	Long-haul: International flights (over 3700 km distance)	1.23205	0.13498	1.36703
Cargo ship	Bulk carrier	0.003539	0.000685	0.004224
	Container ship	0.016143	0.003123	0.019266

Table 3 Construction materials properties data (CIBSE, 2018)

Material	Type	Condition/test (where known)	Density (kg / m³)	Specific heat capacity (J/kg·K)	Thermal conductivity (W/m K)
Asphalt	General 1		1700	1000	0.5
	General 2		2300	1700	1.2
	poured		2100	920	1.2
	reflective coat		2300	1700	1.2
	roofing, mastic		2330	840	1.15
Bitumen	composite, flooring		2400	1000	0.85
	insulation, all types		1000	1700	0.2
Ceramic	glazed		2500	840	1.4
Glass	cellular sheet		140	840	0.048
	foam (130 kg / m³)		130	750	0.056
	foam (140 kg / m³)		140	840	0.052
	solid (soda-lime)		2500	840	1.05
Linoleum	General		1200	1470	0.19
Metals	aluminium		2700	880	230
	aluminium cladding		7680	420	45
	steel		7800	480	45
Polyvinylchloride (pvc)	General		1380	1000	0.16
	tiles		1200	1470	0.19
Carpet/underlay	with cellular rubber underlay		400	1360	0.1
	synthetic		160	2500	0.06
Foam	phenol		30	1400	0.04
	phenol, rigid		110	1470	0.035
	polyisocyanate		45	1470	0.03

	polyurethane		30	1470	0.028
	polyurethane, freon-filled		45	1470	0.03
	polyvinylchloride		37	1470	0.035
	urea formaldehyde		10	1400	0.04
	urea formaldehyde resin		14	1470	0.054
Loose fill/powders	gravel		1840	840	0.36
	sand		2240	840	1.74
Miscellaneous materials	polyurethane, expanded		24	1590	0.023
	polyurethane, unfaced		32	1590	0.023
	aggregate	Undried	2240	840	1.8
	aggregate (sand, gravel or stone)	Oven dried	2240	920	1.3
	building board, tile and lay-in panel		290	590	0.058
	calcium silicate brick		2000	840	1.5
	granolithic		2085	840	0.87
	mud phuska	At 50°C	1620	880	0.52
	tile bedding		2100	650	1.4
	tile hanging		1900	800	0.84
	afzelia, minunga, meranti		850	2070	0.29
	ebonite, expanded		100	1470	0.035
	perlite board, expanded, organic-bonded		16	1260	0.052
	glass fibre board, organic-bonded		100	960	0.036
	weatherboard		650	2000	0.14
Carpet/underlay	polyurethane board, cellular		24	1590	0.023
	polyisocyanurate board		32	920	0.02
	polyisocyanurate board, foil-faced, glass-fibre reinforced		32	920	0.019
	polystyrene, expanded (eps)		23	1470	0.035
	polystyrene, extruded (eps)		35	1470	0.027

	polyvinylchloride (pvc), expanded		100	750	0.04
	silicon		700	1000	0.18
Asbestos-related materials	asbestos cement		1750	840	1.02
	asbestos cement building board		1920	840	0.6
	asbestos cement decking		1500	1050	0.36
	asbestos cement sheet	Conditioned	700	1050	0.36
	asbestos fibre	At 50°C	640	840	0.06
	asbestos mill board	At 50°C	1400	840	0.25
Brick	General 1		1920	840	0.72
	General 2		2080	921	1.31
	aerated		1000	840	0.3
	brickwork, inner leaf		1700	800	0.62
	brickwork, outer leaf		1700	800	0.84
	burned (1300 kg / m³)		1300	840	0.75
	burned (1500 kg / m³)		1500	840	0.85
	burned (1700 kg / m³)		1700	840	1
	mud	At 50°C	1730	880	0.75
	paviour		2000	840	0.96
	reinforced	At 50°C	1920	840	1.1
	tile	At 50°C	1890	880	0.8
Cement/plaster/mortar	cement		1860	840	0.72
	cement blocks, cellular		520	2040	0.33
	cement fibreboard, magnesium oxysulphide binder		350	1300	0.082
	cement mortar (1650 kg / m³)		1650	920	0.72
	cement mortar (1900 kg / m³) - Dry	Dry	1900	840	0.93
	cement mortar (1900 kg / m³) - Moist	Moist	1900	840	1.5
	cement/lime plaster		1600	840	0.8

	cement panels, wood fibres (350 kg / m³) - Dry	Dry	350	1890	0.08
	cement panels, wood fibres (350 kg / m³) - Moist	Moist	350	3040	0.12
	cement panels, wood fibres (400 kg / m³)		400	1470	0.12
	cement panels, wood fibres (1650 kg / m³) - Dry	Dry	1650	840	0.35
	cement plaster (1760 kg / m³)		1760	840	0.72
	cement plaster (1900 kg / m³)		1900	840	1.5
	cement plaster, sand aggregate		1860	840	0.72
	cement screed		2100	650	1.4
	gypsum		1200	840	0.42
	gypsum plaster		1120	960	0.51
	gypsum plaster, perlite aggregate		720	1340	0.22
	gypsum plaster, sand aggregate		1680	840	0.81
	gypsum plasterboard (800 kg / m³)		800	840	0.16
	gypsum plasterboard (1100 kg / m³)		1100	840	0.65
	gypsum plastering		1300	840	0.8
	limestone mortar		1600	840	0.7
	plaster (800 kg / m³)		800	840	0.22
	plaster (950 kg / m³)		950	840	0.35
	plaster (1200 kg / m³)		1200	840	0.52
	plaster ceiling tiles		1120	840	0.38
	plaster, lightweight aggregate		720	840	0.23
	plaster, sand aggregate		1680	840	0.82
	plasterboard		950	840	0.16
	render, synthetic resin, exterior insulation		1100	900	0.7

	rendering (Moisture content 1%)	Moisture content 1%	1430	1000	1.13
	rendering (Moisture content 8%)	Moisture content 8%	1330	1000	0.79
	vermiculite plaster		720	840	0.2
Ceramic/clay tiles	ceramic tiles	Dry	2000	850	1.2
	ceramic floor tiles	Dry	1700	850	0.8
	clay tiles		1900	840	0.85
	clay tile, burnt		2000	840	1.3
	clay tile, hollow, 10.2 mm, | cell		1120	840	0.52
	clay tile, hollow, 20.3 mm, 2 cells		1120	840	0.623
	clay tile, hollow, 32.5 mm, 3 cells		1120	840	0.693
	clay tile, pavior		1920	840	1.803
Concrete blocks/tiles	block, aerated		750	1000	0.24
	block, heavyweight, 300 mm		2240	840	1.31
	block, lightweight, 150 mm		1760	840	0.66
	block, lightweight, 300 mm (1800 kg / m^3)		1800	840	0.73
	block, lightweight, 300 mm (620 kg / m^3)	Dry	620	840	0.24
	block, lightweight, 300 mm (670 kg / m^3)	Dry	670	840	0.25
	block, lightweight, 300 mm (720 kg / m^3)	Dry	720	840	0.26
	block, lightweight, 300 mm (750 kg / m^3)	Dry	750	840	0.3
	block, lightweight, 300 mm 770 kg / m^3)	Dry	770	840	0.28
	block, lightweight, 300 mm (820 kg / m^3)	Dry	820	840	0.29
	block, lightweight, 300 mm (870 kg /	Dry	870	840	0.3

	m³)				
	block, medium-weight, 150 mm		1900	840	0.77
	block, medium-weight, 300 mm (1940 kg / m³)		1940	840	0.83
	block, medium-weight, 300 mm (920 kg / m³)	Dry	920	840	0.31
	block, medium-weight, 300 mm (970 kg / m³)	Dry	970	840	0.32
	block, medium-weight, 300 mm (1050 kg / m³)	Dry	1050	840	0.35
	block, medium-weight, 300 mm (1150 kg / m³)	Dry	1150	840	0.4
	block, hollow, heavyweight, 300 mm		1220	840	1.35
	block, hollow, lightweight, 150 mm		880	840	0.48
	block, hollow, lightweight, 300 mm		780	840	0.76
	block, hollow, medium-weight, 150 mm		1040	840	0.62
	block, hollow, medium-weight, 300 mm		930	840	0.86
	block, partially filled, heavyweight, 300 mm		1570	840	1.35
	block, partially filled, lightweight, 150 mm		1170	840	0.55
	block, partially filled, lightweight,300 mm		1120	840	0.74
	block, partially filled, medium-weight, 150 mm		1330	840	0.64
	block, partially filled, medium-weight,300 mm		1260	840	0.85
	block, perlite-filled, lightweight,150		910	840	0.17

	mm				
	block, perlite-filled, medium-weight,150 mm		1070	840	0.2
	block, with perlite, lightweight,150 mm		1180	840	0.33
	block, with perlite, medium-weight,150 mm		1340	840	0.39
	tiles		2100	840	1.1
Concrete, cast	aerated (500 kg / m³)		500	840	0.16
	aerated (850 kg / m³)		850	840	0.29
	aerated (1200 kg / m³)		1200	840	0.42
	aerated, cellular (400 kg / m³)		400	840	0.15
	aerated, cellular (700 kg / m³)		700	840	0.23
	aerated, cellular (1000 kg / m³)		1000	840	0.7
	aerated, cellular (1300 kg / m³)		1300	840	1.2
	aerated, cement/lime based		580	840	0.21
	cellular (480 kg / m³)		480	840	0.16
	cellular (700 kg / m³)	At 50°C	700	1050	0.19
	cellular bonded		520	2040	0.3
	dense		2200	840	1.7
	compacted (2400 kg / m³)		2400	840	2.2
	dense, reinforced		2300	840	1.9
	compacted (2500 kg / m³)		2500	840	2.3
	expanded clay filling (780 kg / m³)		780	840	0.26
	expanded clay filling (1400kg / m³)		1400	840	0.6
	foamed (320 kg / m³)	At 50°C	320	920	0.07
	foamed (400 kg / m³)	At 50°C	400	920	0.08
	foamed (700 kg / m³)	At50°C	700	920	0.15
	foam slag		1040	960	0.25

glass reinforced		1950	840	0.9
heavyweight - Dry	Dry	2000	840	1.3
heavyweight - Moist	Moist	2000	840	1.7
lightweight - (620 kg / m³) - Dry	Dry	620	840	0.2
lightweight - (750 kg / m³) - Dry	Dry	750	840	0.25
lightweight - (670 kg / m³) - Dry	Dry	670	840	0.21
lightweight - (720 kg / m³) - Dry	Dry	720	840	0.22
lightweight - (770 kg / m³) - Dry	Dry	770	840	0.23
lightweight - (820 kg / m³) - Dry	Dry	820	840	0.24
lightweight - (870 kg / m³) - Dry	Dry	870	840	0.25
lightweight - (750 kg / m³) - Moist	Moist	750	840	0.43
lightweight - (770 kg / m³) - Moist	Moist	770	840	0.38
lightweight - (820 kg / m³) - Moist	Moist	820	840	0.4
lightweight - (870 kg / m³) - Moist	Moist	870	840	0.43
lightweight - (200 kg / m³)		200	840	0.08
lightweight - (300 kg / m³)		300	840	0.12
lightweight - (500 kg / m³)		500	840	0.17
lightweight - (700 kg / m³)		700	840	0.23
medium-weight - (1050 kg / m³) - Dry (1)	Dry	1050	840	0.32
medium-weight - (1150 kg / m³) - Dry	Dry	1150	840	0.37
medium-weight - (1350 kg / m³) - Dry	Dry	1350	840	0.59
medium-weight - (1650 kg / m³) - Dry	Dry	1650	840	0.84
medium-weight - (1050 kg / m³) - Dry (2)	Dry	1050	840	0.37
medium-weight - (920 kg / m³) - Dry	Dry	920	840	0.27
medium-weight - (980 kg / m³) - Dry	Dry	980	840	0.29
medium-weight - (1050 kg / m³) - Moist	Moist	1050	840	0.59

	medium-weight - (1000 kg / m³)		1000	840	0.5
	medium-weight - (1300 kg / m³)		1300	840	0.8
	medium-weight - (1600 kg / m³)		1600	840	1.2
	medium-weight - (1900kg / m³)		1900	840	1.4
	medium-weight, with lime	At 50°C	1650	880	0.73
	no fines		1800	840	0.96
	residuals of iron works (1000 kg / m³)		1000	840	0.35
	residuals of iron works (1300 kg / m³)		1300	840	0.45
	residuals of iron works (1600 kg / m³)		1600	840	0.7
	residuals of iron works (1900 kg / m³)		1900	840	1
	roofing slab, aerated		500	840	0.16
	vermiculite aggregate		450	840	0.17
	very lightweight (370 kg / m³)		370	840	0.14
	very lightweight (420 kg / m³)		420	840	0.15
	very lightweight (470 kg / m³)		470	840	0.16
	very lightweight (520 kg / m³)		520	840	0.17
	very lightweight (570 kg / m³)		570	840	0.18
	very lightweight (350 kg / m³)		350	840	0.12
	very lightweight (600 kg / m³)		600	840	0.18
Masonry	block, lightweight (470 kg / m³)		470	840	0.19
	block, lightweight (520 kg / m³)		520	840	0.2
	block, lightweight (570 kg / m³)		570	840	0.22
	block, lightweight (600 kg / m³)		600	840	0.22
	block, medium-weight (1350 kg / m³) - Dry	Dry	1350	840	0.6
	block, medium-weight (1650 kg / m³) - Dry	Dry	1650	840	0.85
	block, medium-weight (1800 kg / m³) - Dry	Dry	1800	840	1.3

	heavyweight (1850 kg / m³) - Dry (1)	Dry	1850	840	0.9
	heavyweight (1850 kg / m³) - Dry (2)	Dry	1850	840	0.73
	heavyweight (1950 kg / m³) - Dry	Dry	1950	840	0.79
	heavyweight (2050 kg / m³) - Dry	Dry	2050	840	0.9
	heavyweight (1650 kg / m³) - Dry	Moist	1650	840	0.81
	lightweight (750 kg / m³) - Dry	Dry	750	840	0.22
	lightweight (850 kg / m³) - Dry (1)	Dry	850	840	0.27
	lightweight (850 kg / m³) - Dry (2)	Dry	850	840	0.24
	lightweight (950 kg / m³) - Dry	Dry	950	840	0.27
	medium-weight (1050 kg / m³) - Dry	Dry	1050	840	0.32
	medium-weight (1300 kg / m³) - Dry	Dry	1300	840	0.54
	medium-weight (1150 kg / m³) - Dry	Dry	1150	840	0.37
	medium-weight (1250 kg / m³) - Dry	Dry	1250	840	0.42
	medium-weight (1350 kg / m³) - Dry	Dry	1350	840	0.45
	medium-weight (1450 kg / m³) - Dry	Dry	1450	840	0.49
	medium-weight (1550 kg / m³) - Dry	Dry	1550	840	0.54
	quarry stones, calcareous	Dry	2200	840	1.4
Roofing materials	built-up roofing		1120	1470	0.16
	roof tile		1900	800	0.84
	tile, terracotta		1700	840	0.81
Soil	alluvial clay, 40% sands		1960	840	1.21
	black cotton clay, Indore		1680	880	0.61
	black cotton clay, Madras		1900	880	0.74
	diatomaceous Kieselguhr or infusorial earth	Moisture content 9%	480	180	0.09
	earth, common		1460	880	1.28
	earth, gravel-based		2050	180	0.52
Stone	basalt		2880	840	3.49
	gneiss		2880	840	3.49

granite		2880	840	3.49
granite, red		2650	900	29
hard stone (unspecified) - (2880 kg / m³)		2880	840	3.49
hard stone (unspecified) - (2750 kg / m³)		2750	840	2.9
limestone - (2180 kg / m³)		2180	720	1.5
limestone - (2750 kg / m³)		2750	840	29
limestone - (2420 kg / m³)	At 50°C	2420	840	1.8
marble		2750	840	2.9
marble - Dry	Dry	2750	840	2.91
marble - Moist	Moist	2750	840	3.49
marble, white		2500	880	2
petit granit (blue stone) - Dry	Dry	2700	840	2.91
petit granit (blue stone) - Moist	Moist	2700	840	3.49
porphyry		2880	840	3.49
sandstone - (2200 kg / m³)		2200	710	1.83
sandstone - (2150 kg / m³) (1)		2150	840	3
sandstone - (2150 kg / m³) (2)		2150	840	1.3
sandstone - (2150 kg / m³) (3)		2150	840	5
sandstone tiles	Dry	2000	840	1.2
slate (1600 kg / m³)		1600	1470	1.44
slate (2750 kg / m³)	At 50°C	2750	840	1.72
slate shale		2700	840	2.1
white calcareous stone - Firm, moist	Firm, moist	2350	840	2.09
white calcareous stone - Firm, dry	Firm, dry	2350	840	1.74
white calcareous stone - Hard, moist	Hard, moist	2550	840	2.68
white calcareous stone - Hard, dry	Hard, dry	2550	840	2.21
tufa, soft - Dry	Dry	1300	840	0.35

	tufa, soft - Moist	Moist	1300	1260	0.5
Cardboard/paper	bitumen impregnated paper		1090	1000	0.06
	laminated paper		480	1380	0.072
Cloth/carpet/felt	bitumen/felt layers		1700	1000	0.5
	carpet, simulated wool		200	1360	0.06
	carpet, Wilton		190	1360	0.06
	felt, semi-rigid, organic bonded - (48 kg / m³)	At 37.7°C	48	710	0.035
	felt, semi-rigid, organic bonded - (88 kg / m³)	At 37.7 °C	88	710	0.039
	jute felt	At 50°C	290	880	0.042
	jute fibre	At 50°C	330	1090	0.067
	wool felt underlay		160	1360	0.04
Cork	board		160	1890	0.04
	expanded		150	1760	0.044
	expanded, impregnated		150	1760	0.043
	slab (160 kg / m³)		160	960	0.043
	slab (300kg / m³)		300	960	0.055
	tiles	Conditioned	530	1800	0.08
Grass/straw materials	straw board	At 50°C	310	1300	0.057
	straw fibreboard or slab		300	2100	0.1
	straw thatch		240	180	0.07
Organic materials and their derivatives	coconut pith insulation				
	board	At 50°C	520	1090	0.06
	coir board	At 50°C	97	1000	0.038
	flax shive, cement-bonded board		520	1470	0.1
	flax shive, resin-bonded board		500	1880	0.12
	rice husk	At 50°C	120	1000	0.051
	vegetable fibre sheathing		290	1300	0.055

Woods	fir, pine		510	1380	0.12
	hardwood (unspecified) - (90 kg / m³)		90	2810	0.05
	hardwood (unspecified) - (700 kg / m³) - Dry	Dry	700	1880	0.17
	hardwood (unspecified) - (800 kg / m³)		800	1880	0.23
	maple, oak and similar hardwoods		720	1260	0.16
	oak, radial		700	2390	0.19
	oak, beech, ash, walnut meranti - Moist	Moist	650	3050	0.23
	oak, beech, ash, walnut meranti - Dry	Dry	650	2120	0.17
	pine, pitch pine - Dry	Dry	650	2120	0.17
	pine, pitch pine - Moist	Moist	650	3050	0.23
	red fir, Oregon fir - Dry	Dry	520	2280	0.14
	red fir, Oregon fir - Moist	Moist	520	3440	0.17
	resinous woods (spruce, sylvester pine)	Dry	530	1880	0.12
	softwood - (510 kg / m³)		510	1380	0.12
	softwood - (630 kg / m³)		630	2760	0.13
	softwood - (550 kg / m³)		550	1880	0.14
	timber - (480 kg / m³)	At 50°C	480	1680	0.072
	timber - (720 kg / m³)	At 50°C	720	1680	0.14
	timber flooring		650	1200	0.14
	willow, North Canadian gaboon		420	2400	0.12
	willow, birch, soft beech		520	2280	0.14
Wood derivatives	General - Moist	Moist	520	3440	0.17
	cellulosic insulation, loose fill		43	1380	0.042

	chipboard	At 50°C	430	1260	0.067
	chipboard, bonded with PF - Dry	Dry	650	2340	0.12
	chipboard, bonded with PF - Moist	Moist	650	5020	0.25
	chipboard, bonded with uF - Dry	Dry	630	2260	0.12
	chipboard, bonded with uF - Moist	Moist	630	5020	0.25
	chipboard, bonded with melamine - Dry	Dry	630	2260	0.12
	chipboard, bonded with melamine - Moist	Moist	630	5020	0.25
	chipboard, perforated	At 50°C	350	1260	0.066
	flooring blocks		650	1200	0.14
	hardboard (600 kg / m³)		600	2000	0.08
	hardboard (880 kg / m³)		880	1340	0.12
	hardboard (1000 kg / m³)		1000	1680	0.29
	multiplex, beech	Dry	650	2300	0.15
	multiplex, North Canadian gaboon	Dry	450	2300	0.12
	multiplex, red fir - Dry	Dry	550	2300	0.13
	multiplex, red fir - Moist	Moist	550	2300	0.21
	particle board (750 kg / m³)		750	1300	0.098
	particle board (1000 kg / m³)		1000	1300	0.17
	particle board (800 kg / m³)		800	1300	0.12
	plywood (540 kg / m³)		540	1210	0.12
	plywood (700 kg / m³)		700	1420	0.15
	sawdust	At 50°C	190	1000	0.051
	softboard	At 50°C	250	1300	0.047
	wallboard	At 50°C	260	1260	0.047
	wood chip board, cement-bonded		530	1470	0.15
	wood fibres, compressed		320	100	0.055
	wood (soft) fibre, loose fill		45	1380	0.043

	wood particle panels (300 kg / m³)		300	1880	0.09
	wood particle panels (500 kg / m³)		500	1880	0.12
	wood particle panels (700 kg / m³)		700	1880	0.14
	wood particle panels (1000 kg / m³) - Hard	Hard	1000	1990	0.29
	wood particle panels (250 kg / m³) - Soft	Soft	250	2520	0.08
	wood shingle		510	1260	0.12
	woodwool board, cement-bonded (400 kg / m³)	At 50°C	400	1130	0.081
	woodwool board, cement-bonded (670kg / m³)	At 50°C	670	1130	0.11
	woodwool roofing slabs		500	1000	0.1
	woodwool, xylolite cement slabs		450	1470	0.11
	woodwool		500	1000	0.1

Table 4 U-values criteria for windows (CIBSE, 2018)

Frames	Types	Indicative U-values (W/m²·K) for windows				Adjustments to U-values
		Gap between panes				
		6mm	12mm	16mm	Not applicable	Roof light
Wood or PVCu frames	Windows and doors , single-glazed	#N/A	#N/A	#N/A	4.8	0.5
	Double glazing (air filled)	3.1	2.8	2.7	#N/A	0.3
	Double glazing (low-E, εn = 0.2, air filled)	2.7	2.2	2.1	#N/A	0.3
	Double glazing (low-E, εn = 0.15, air filled)	2.7	2.2	2	#N/A	0.3
	Double glazing (low-E, εn = 0.1, air filled)	2.6	2.1	1.9	#N/A	0.3
	Double glazing (low-E, εn = 0.05, air filled)	2.6	2	1.8	#N/A	0.3
	Double glazing (argon filled)	2.9	2.7	2.6	#N/A	0.3
	Double glazing (low-E, εn = 0.2,argon filled)	2.5	2.1	2	#N/A	0.3
	Double glazing (low-E, εn = 0.15argon filled)	2.4	2	1.9	#N/A	0.3
	Double glazing (low-E, εn = 0.1, argon filled)	2.3	1.9	1.8	#N/A	0.3
	Double glazing (low-E, εn = 0.05, argon filled)	2.3	1.8	1.7	#N/A	0.3
	Triple glazing (air filled)	2.4	2.1	2	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, air filled)	2.1	1.7	1.6	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, air filled)	2.1	1.7	1.6	#N/A	0.2
	Triple glazing (low-E, εn = 0.1, air filled)	2	1.6	1.5	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, air filled)	1.9	1.5	1.4	#N/A	0.2
	Triple glazing (argon-filled)	2.2	2	1.9	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, argon filled)	1.9	1.6	1.5	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, argon filled)	1.8	1.5	1.4	#N/A	0.2
	Triple glazing (low-E, εn = 0.1, argon filled)	1.8	1.5	1.4	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, argon filled)	1.7	1.4	1.3	#N/A	0.2
Metal frames (4mm thermal break)	Windows and doors , single-glazed	#N/A	#N/A	#N/A	5.7	0.5
	Double glazing (air filled)	3.7	3.4	3.3	#N/A	0.3
	Double glazing (low-E, εn = 0.2, air filled)	3.3	2.8	2.6	#N/A	0.3

	Double glazing (low-E, εn = 0.15, air filled)	3.3	2.7	2.5	#N/A	0.3
	Double glazing (low-E, εn = 0.1, air filled)	3.2	2.6	2.4	#N/A	0.3
	Double glazing (low-E, εn = 0.05, air filled)	3.2	2.5	2.3	#N/A	0.3
	Double glazing (argon filled)	3.5	3.3	3.2	#N/A	0.3
	Double glazing (low-E, εn = 0.2,argon filled)	3	2.6	2.5	#N/A	0.3
	Double glazing (low-E, εn = 0.15argon filled)	3	2.5	2.4	#N/A	0.3
	Double glazing (low-E, εn = 0.1, argon filled)	2.9	2.4	2.3	#N/A	0.3
	Double glazing (low-E, εn = 0.05, argon filled)	2.8	2.2	2.1	#N/A	0.3
	Triple glazing (air filled)	2.9	2.6	2.5	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, air filled)	2.6	2.1	2	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, air filled)	2.5	2.1	2	#N/A	0.2
	Triple glazing (low-E, εn = 0.1, air filled)	2.5	2	1.9	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, air filled)	2.4	1.9	1.8	#N/A	0.2
	Triple glazing (argon-filled)	2.8	2.5	2.4	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, argon filled)	2.3	2	1.9	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, argon filled)	2.3	1.9	1.8	#N/A	0.2
	Triple glazing (low-E, εn = 0.1, argon filled)	2.2	1.9	1.8	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, argon filled)	2.2	1.8	1.7	#N/A	0.2
Metal frames (0mm thermal break)	Windows and doors , single-glazed	#N/A	#N/A	#N/A	6	0.5
	Double glazing (air filled)	4	3.7	3.6	#N/A	0.3
	Double glazing (low-E, εn = 0.2, air filled)	3.6	3.1	2.9	#N/A	0.3
	Double glazing (low-E, εn = 0.15, air filled)	3.6	3	2.8	#N/A	0.3
	Double glazing (low-E, εn = 0.1, air filled)	3.5	2.9	2.7	#N/A	0.3
	Double glazing (low-E, εn = 0.05, air filled)	3.5	2.8	2.6	#N/A	0.3
	Double glazing (argon filled)	3.8	3.6	3.5	#N/A	0.3
	Double glazing (low-E, εn = 0.2,argon filled)	3.3	2.9	2.8	#N/A	0.3
	Double glazing (low-E, εn = 0.15argon filled)	3.3	2.8	2.7	#N/A	0.3
	Double glazing (low-E, εn = 0.1, argon filled)	3.2	2.7	2.6	#N/A	0.3
	Double glazing (low-E, εn = 0.05, argon filled)	3.1	2.5	2.4	#N/A	0.3
	Triple glazing (air filled)	3.2	2.9	2.8	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, air filled)	2.9	2.4	2.3	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, air filled)	2.8	2.4	2.3	#N/A	0.2

	Triple glazing (low-E, εn = 0.1, air filled)	2.8	2.3	2.2	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, air filled)	2.7	2.2	2.1	#N/A	0.2
	Triple glazing (argon-filled)	3.1	2.8	2.7	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, argon filled)	2.6	2.3	2.2	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, argon filled)	2.6	2.2	2.1	#N/A	0.2
	Triple glazing (low-E, εn = 0.1, argon filled)	2.5	2.2	2.1	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, argon filled)	2.5	2.1	2	#N/A	0.2
Metal frames (8mm thermal break)	Windows and doors , single-glazed	#N/A	#N/A	#N/A	5.6	0.5
	Double glazing (air filled)	3.6	3.3	3.2	#N/A	0.3
	Double glazing (low-E, εn = 0.2, air filled)	3.2	2.7	2.5	#N/A	0.3
	Double glazing (low-E, εn = 0.15, air filled)	3.2	2.6	2.4	#N/A	0.3
	Double glazing (low-E, εn = 0.1, air filled)	3.1	2.5	2.3	#N/A	0.3
	Double glazing (low-E, εn = 0.05, air filled)	3.1	2.4	2.2	#N/A	0.3
	Double glazing (argon filled)	3.4	3.2	3.1	#N/A	0.3
	Double glazing (low-E, εn = 0.2,argon filled)	2.9	2.5	2.4	#N/A	0.3
	Double glazing (low-E, εn = 0.15argon filled)	2.9	2.4	2.3	#N/A	0.3
	Double glazing (low-E, εn = 0.1, argon filled)	2.8	2.3	2.2	#N/A	0.3
	Double glazing (low-E, εn = 0.05, argon filled)	2.7	2.1	2	#N/A	0.3
	Triple glazing (air filled)	2.8	2.5	2.4	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, air filled)	2.5	2	1.9	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, air filled)	2.4	2	1.9	#N/A	0.2
	Triple glazing (low-E, εn = 0.1, air filled)	2.4	1.9	1.8	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, air filled)	2.3	1.8	1.7	#N/A	0.2
	Triple glazing (argon-filled)	2.7	2.4	2.3	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, argon filled)	2.2	1.9	1.8	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, argon filled)	2.2	1.8	1.7	#N/A	0.2
	Triple glazing (low-E, εn = 0.1, argon filled)	2.1	1.8	1.7	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, argon filled)	2.1	1.7	1.6	#N/A	0.2
Metal frames (12mm thermal break)	Windows and doors , single-glazed	#N/A	#N/A	#N/A	5.5	0.5
	Double glazing (air filled)	3.5	3.2	3.1	#N/A	0.3
	Double glazing (low-E, εn = 0.2, air filled)	3.1	2.6	2.4	#N/A	0.3

	Double glazing (low-E, εn = 0.15, air filled)	3.1	2.5	2.3	#N/A	0.3
	Double glazing (low-E, εn = 0.1, air filled)	3	2.4	2.2	#N/A	0.3
	Double glazing (low-E, εn = 0.05, air filled)	3	2.3	2.1	#N/A	0.3
	Double glazing (argon filled)	3.3	3.1	3	#N/A	0.3
	Double glazing (low-E, εn = 0.2,argon filled)	2.8	2.4	2.3	#N/A	0.3
	Double glazing (low-E, εn = 0.15argon filled)	2.8	2.3	2.2	#N/A	0.3
	Double glazing (low-E, εn = 0.1, argon filled)	2.7	2.2	2.1	#N/A	0.3
	Double glazing (low-E, εn = 0.05, argon filled)	2.6	2	1.9	#N/A	0.3
	Triple glazing (air filled)	2.7	2.4	2.3	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, air filled)	2.4	1.9	1.8	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, air filled)	2.3	1.9	1.8	#N/A	0.2
	Triple glazing (low-E, εn = 0.1, air filled)	2.3	1.8	1.7	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, air filled)	2.2	1.7	1.6	#N/A	0.2
	Triple glazing (argon-filled)	2.6	2.3	2.2	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, argon filled)	2.1	1.8	1.7	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, argon filled)	2.1	1.7	1.6	#N/A	0.2
	Triple glazing (low-E, εn = 0.1, argon filled)	2	1.7	1.6	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, argon filled)	2	1.6	1.5	#N/A	0.2
Metal frames (20mm thermal break)	Windows and doors , single-glazed	#N/A	#N/A	#N/A	5.4	0.5
	Double glazing (air filled)	3.4	3.1	3	#N/A	0.3
	Double glazing (low-E, εn = 0.2, air filled)	3	2.5	2.3	#N/A	0.3
	Double glazing (low-E, εn = 0.15, air filled)	3	2.4	2.2	#N/A	0.3
	Double glazing (low-E, εn = 0.1, air filled)	2.9	2.3	2.1	#N/A	0.3
	Double glazing (low-E, εn = 0.05, air filled)	2.9	2.2	2	#N/A	0.3
	Double glazing (argon filled)	3.2	3	2.9	#N/A	0.3
	Double glazing (low-E, εn = 0.2,argon filled)	2.7	2.3	2.2	#N/A	0.3
	Double glazing (low-E, εn = 0.15argon filled)	2.7	2.2	2.1	#N/A	0.3
	Double glazing (low-E, εn = 0.1, argon filled)	2.6	2.1	2	#N/A	0.3
	Double glazing (low-E, εn = 0.05, argon filled)	2.5	1.9	1.8	#N/A	0.3
	Triple glazing (air filled)	2.6	2.3	2.2	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, air filled)	2.3	1.8	1.7	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, air filled)	2.2	1.8	1.7	#N/A	0.2

	Triple glazing (low-E, εn = 0.1, air filled)	2.2	1.7	1.6	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, air filled)	2.1	1.6	1.5	#N/A	0.2
	Triple glazing (argon-filled)	2.5	2.2	2.1	#N/A	0.2
	Triple glazing (low-E, εn = 0.2, argon filled)	2	1.7	1.6	#N/A	0.2
	Triple glazing (low-E, εn = 0.15, argon filled)	2	1.6	1.5	#N/A	0.2
	Triple glazing (low-E, εn = 0.1, argon filled)	1.9	1.6	1.5	#N/A	0.2
	Triple glazing (low-E, εn = 0.05, argon filled)	1.9	1.5	1.4	#N/A	0.2

Table 5 U-values criteria for ground floors (CIBSE, 2018)

Soil types	Ground floor perimeter (P) / Ground floor area (A)	**U-value (W/m^2 K) for stated thermal resistance (m^2 K W^{-1})**				
		0	0.5	1	1.5	2
Clay soil	0.05	0.13	0.11	0.1	0.09	0.08
	0.1	0.22	0.18	0.16	0.14	0.13
	0.15	0.3	0.24	0.21	0.18	0.17
	0.2	0.37	0.29	0.25	0.22	0.19
	0.25	0.44	0.34	0.28	0.24	0.22
	0.3	0.49	0.38	0.31	0.27	0.23
	0.35	0.55	0.41	0.34	0.29	0.25
	0.4	0.6	0.44	0.36	0.3	0.26
	0.45	0.65	0.47	0.38	0.32	0.27
	0.5	0.7	0.5	0.4	0.33	0.28
	0.55	0.74	0.52	0.41	0.34	0.28
	0.6	0.78	0.55	0.43	0.35	0.29
	0.65	0.82	0.57	0.44	0.35	0.3
	0.7	0.86	0.59	0.45	0.36	0.3
	0.75	0.89	0.61	0.46	0.37	0.31
	0.8	0.93	0.62	0.47	0.37	0.32
	0.85	0.96	0.64	0.47	0.38	0.32
	0.9	0.99	0.65	0.48	0.39	0.32
	0.95	1.02	0.66	0.49	0.39	0.33
	1	1.05	0.68	0.5	0.4	0.33
Sand or gravel	0.05	0.16	0.14	0.12	0.11	0.1
	0.1	0.28	0.22	0.19	0.18	0.16
	0.15	0.38	0.3	0.25	0.23	0.2
	0.2	0.47	0.36	0.3	0.27	0.23
	0.25	0.55	0.41	0.33	0.29	0.25
	0.3	0.63	0.46	0.37	0.32	0.26
	0.35	0.7	0.5	0.39	0.34	0.28
	0.4	0.76	0.53	0.42	0.36	0.29
	0.45	0.82	0.56	0.43	0.37	0.3
	0.5	0.88	0.59	0.45	0.38	0.31
	0.55	0.93	0.62	0.47	0.39	0.31
	0.6	0.98	0.64	0.48	0.40	0.32

	0.65	1.03	0.66	0.49	0.41	0.33
	0.7	1.07	0.68	0.5	0.42	0.33
	0.75	1.12	0.7	0.51	0.43	0.34
	0.8	1.16	0.72	0.52	0.43	0.34
	0.85	1.19	0.73	0.53	0.44	0.35
	0.9	1.23	0.75	0.54	0.45	0.35
	0.95	1.27	0.76	0.54	0.45	0.35
	1	1.3	0.77	0.55	0.45	0.35
Homogeneous rock	0.05	0.27	0.21	0.18	0.17	0.15
	0.1	0.45	0.34	0.28	0.25	0.22
	0.15	0.61	0.43	0.35	0.31	0.26
	0.2	0.74	0.51	0.4	0.34	0.28
	0.25	0.86	0.58	0.44	0.37	0.3
	0.3	0.97	0.63	0.47	0.40	0.32
	0.35	1.07	0.66	0.5	0.42	0.33
	0.4	1.16	0.72	0.52	0.43	0.34
	0.45	1.25	0.75	0.53	0.44	0.35
	0.5	1.33	0.78	0.55	0.45	0.35
	0.55	1.4	0.8	0.56	0.46	0.36
	0.6	1.47	0.82	0.58	0.48	0.37
	0.65	1.53	0.84	0.59	0.48	0.37
	0.7	1.59	0.86	0.6	0.49	0.37
	0.75	1.64	0.87	0.61	0.50	0.38
	0.8	1.69	0.89	0.62	0.50	0.38
	0.85	1.74	0.91	0.62	0.50	0.38
	0.9	1.79	0.92	0.63	0.51	0.39
	0.95	1.83	0.93	0.64	0.52	0.39
	1	1.87	0.95	0.64	0.52	0.39

Table 6 Monthly maximum and minimum temperatures (°C) for selected Saudi Arabian cities in 2019 (General Authority for Statistics, 2019e)

Zones	Cities	Temperature (°C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	RIYADH	Maximum temperature	23.4	22.9	26.2	31.3	38.5	43.5	43.9	44.3	43.1	38	28.4	24
		Minimum Temperature	11.2	11.4	13.3	18.6	24.9	28.5	28.7	27.3	25.8	22	15.4	10.7
	JEDDAH	Maximum temperature	28.9	28.9	29.5	32.7	37.2	38.6	39	37.8	36.3	35.2	33.4	29.8
		Minimum Temperature	21.3	21.4	20.7	23.6	28.5	29.9	29.5	30.6	28.8	28.3	25.1	22
	MAKKAH	Maximum temperature	32	31.6	33.6	38.2	42.1	44.4	43.8	42	42.9	38.8	35.3	31.9
		Minimum Temperature	19.5	19.8	19.8	24.4	27.7	30.3	29.9	29	23.3	26	23.3	20.7
	MEDIAN	Maximum temperature	25.7	25.2	28.1	33.9	40.2	43.4	43.2	42.6	43.2	37.8	31.3	26.4
		Minimum Temperature	14.7	14.5	15.4	20.6	26.8	31	31	30.6	30	25.9	19.6	14.5
	GASSIM	Maximum temperature	22.3	21.8	26.3	30.8	38.8	44.2	44.3	43.7	42.9	37.1	26.9	23.7
		Minimum Temperature	9.2	8.9	10.9	16	23	26.8	26.2	25.9	24.9	21.5	14.1	8.6
	DAMMAM	Maximum temperature	23.9	22.8	26.5	32.6	40.7	45.4	44.2	45.3	43.2	38.9	29	23.9
		Minimum Temperature	12.2	12.3	13.7	19.7	24.9	28.6	29.6	29.1	26.5	24.4	17.1	13.5
2	KHAMIS MUSHAIT	Maximum temperature	24.8	23.6	24.2	27.4	29	33	34.4	31.9	32	28.3	24.9	22.2
		Minimum Temperature	10.4	12	13.6	15.5	16.3	19.1	20.1	18.3	17.8	14.9	12.3	10.5
	TABUK	Maximum temperature	19.4	19.9	22.7	28.2	36.5	39.2	39.2	39.1	38.5	33.2	25.8	20.1
		Minimum Temperature	6.2	8.4	9.6	13.9	21.2	25	25.4	24.8	23.2	19.9	12.7	6.5
3	ABHA	Maximum temperature	23.7	22.5	23.3	26.6	27.6	31.5	32.3	30.3	31	25.8	22.2	19.8
		Minimum Temperature	9.4	11.4	13	14.9	15.7	18	19	16.8	16.5	13.6	11.1	10

Table 7 Cooling and heating degree days (°C) for selected Saudi Arabian cities (ASHRAE, 2017)

Zones	Saudi Arabia - City	Latitude	Longitude	Elevation (m)	Heating Degree-Days (HDD) base 18.3 °C	Colling Degree-Days (CDD) base 18.3 °C	Heating Degree-Days (HDD) base 10 °C	Colling Degree-Days (CDD) base 10 °C
1	RIYADH	24.710N	46.725E	635	276	3366	7	6138
	JEDDAH	21.680N	39.157E	15	1	3813	0	6853
	MAKKAH	21.433N	39.767E	240	1	4830	0	7872
	MEDIAN	24.553N	39.705E	656	76	3803	0	6769
	GASSIM	26.300N	43.767E	648	412	2993	18	5642
	DAMMAM	26.433N	49.800E	12	213	3463	2	6294
2	KHAMIS MUSHAIT	18.297N	42.804E	2066	313	1042	0	3772
	TABUK	28.365N	36.619E	778	657	2133	36	4553
3	ABHA	18.240N	42.657E	2090	480	819	1	3382

Appendix E. User manual (beta version)

A Framework for Assessing the Environmentally Sustainable and Resilience Performance of Domestic Building Materials in Saudi Arabia

An explanation of the functioning of the framework

(Beta version)

(Beta version)

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(Beta version)

1. Introduction

1.1. Background

The aim of this research is to develop a framework (RSAF) for assessing both the resilience and (environmental) sustainability of structural materials in constructing residential buildings in Saudi Arabia. The purpose of the framework is to determine the usage of structural building materials in Saudi Arabia's domestic buildings to minimise carbon emissions and reduce energy consumption. Additional information about this research can be obtained from the conference paper attached to this document[1].

This document serves as a guide for using the framework[2]. A case study tutorial is presented as well to ensure that potential users can fully understand how the case study will be implemented. The first part of the brief description about the framework comprises the "input" which includes four stages. Each stage is composed of certain steps to be followed. The second part comprises the "output" which summarises the results in graphs and tables.

Although the developed framework is intended to be used for Saudi Arabian domestic buildings, it may be used in a generic fashion for other types of buildings in different regions. However, note that certain factors may affect the final results (outcome), especially stage 3 which calculates the annual consumption (energy demand) for cooling or heating load, as the framework is currently designed for cities in Saudi Arabia only.

1.2. Framework requirements

The following applications must be installed on the PC or laptop of a user of the framework:

1- Microsoft excel program (version 2016 and higher)[3]
2- PDF file reader application (such as Adobe Acrobat).

In order to use this framework as intended, the following information about the proposed domestic building should be available before implementation of the framework:

1- Domestic building plans and dimensions;
2- Location of the building;
3- Soil types at the location of the building;
4- Construction materials (types and quantities);
5- Modes transport and gate-to-cradle (from the factory gate to the end of the useful of the building) distances (where available);
6- Detailing about wall and roof construction;

[1] Almulhim, M.S., Hunt, D.V.L., and Rogers C.D.F. (2018) Framework for Assessing the Environmentally Sustainable and Resilience Performance of Domestic Building Materials in Saudi Arabia. Proceedings of the 2nd International Conference on Sustainability, Human Geography and Environment. 28 November - 2 December, Kraków, Poland. pp. 210-14.
[2] This document presents a beta version of the framework and its guide (user manual) for the purpose of obtaining feedback from potential users in Saudi Arabia.
[3] This requirement ensures that the file formats will not change when an older version is used.

7- Glazing types (e.g. windows or skylights);

A user may utilise the framework even if some of the information listed above is not available. In such cases, appropriate assumptions should be made and suitable justification provided. Note that the accuracy of the results is highly dependent on the availability of the above-mentioned information as well as the choices made by the users while implementing the framework.

2. User manual and tutorial

2.1. General instructions

A. Before using the framework, and as a general rule of thumb, the user should either fill or make selections in the white-coloured cells only; no changes should be made to the light blue-coloured cells. The cells will be filled automatically based on your selections. An example of the cells forms is shown in Figure 1.

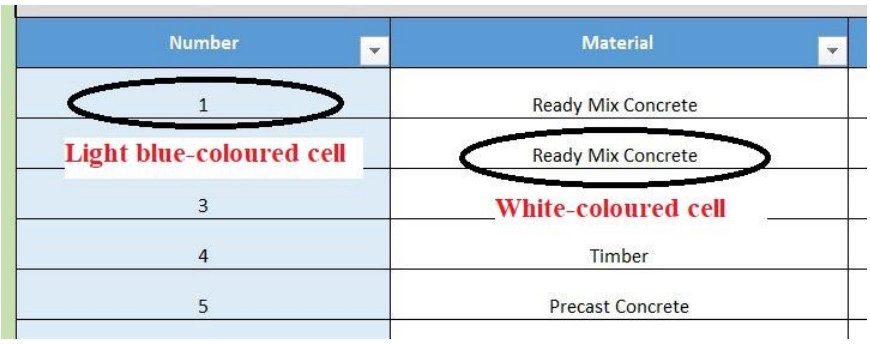

Figure 1: General instructions (colours of the forms)

B. The user must make a series of material selection choices while filling the forms (this will be elucidated through the use of an example. These selections will be based directly on his/her decisions and will undoubtedly be influenced by the accuracy of the available data for the proposed house (existing or planned). Users always have the option to change their decisions or selections, and reverse the calculations (results). This allows the user to undertake multiple runs and look at the environmental and resilience impacts.

C. It is recommended that the user consult the framework (Excel application) at the same time as reading this document so as to facilitate understanding of how the framework should be applied. Moreover the user will gain more information about the details, decisions, assumptions and results of the example case study.

D. To get the full benefit of the framework and its potential for future development it is recommended that the user apply his/her own case study / project.

2.2. Part 1: Information and details about the proposed house building (inputs)

The following stages explain how the framework functions. A case study[4] is also provided as an illustration. This housing project will be built in Dammam, Saudi Arabia. The total floor space will be 889.7 m^2, and detailed designs of the house design, floor plan and elevations are attached in the appendices. The house will be composed of ground, first and penthouse floors. The building will be a concrete structure using a two-way ribbed slab system. The construction materials are specified in the proposed design, and the usage, quantities and specifications of the materials are summarised in Table 1, in line with the design plans. The total weight of the materials amounts to around 3326911.24 kg.

Table 1: Proposed construction materials in the residential building design

Material	Type	Quantity (Unit)	Quantity (kg)[5]	Specifications and Purpose
Ready mix concrete	(25-30 MPa) - 100% Portland cement (CEM I)	31.57 m^3	76083.7	Plain concrete for blinding (below foundations , ground beams)
Ready mix concrete	(28-35 MPa) - 100% Portland cement (CEM I)	772.79 m^3	1870151.8	Reinforced concrete for foundations, beams, columns, slabs, stairs.
Cement	Mortar (1:3 cement: sand mix)	130.13 m^3	247247	Top of floor slab to receive finishes, concrete blocks insulation and plastering for exterior and internal walls.
Steel	Reinforcement steel	-	37912.10	Steel rebar for concrete structure elements.
Timber	Plywood	3923.83 m^2	32960.17	Formworks in construction process for concrete structure elements.
Precast Concrete	(25-30 MPa) - 100% Portland cement (CEM I)	5.76 m^2	2082.24	Exterior walls cladding
Block	Autoclaved aerated block	7335 pieces	88020	Filling the empty spaces in the two way ribbed slabs.
Block	Concrete block: (12 MPa)	2819 pieces	95846	Masonry solid blocks for Foundation walls

[4] In order to provide the needed information in as brief a manner as possible, the case study has been presented briefly. All the significant details of the case study have been covered in the attached framework.

[5] Density of the materials extracted from (Asif, 2017; CIBSE, 2018), to calculate with kg.

Table 2: Proposed construction materials in the residential building design (Cont.)

Material	Type	Quantity (Unit)	Quantity (kg)[6]	Specifications and Purpose
Block	Concrete block: (8 MPa)	27226 pieces	787160	Masonry hollow block for external and internal walls
Insulation	Expanded Polystyrene[2]	16.61 m^3	531.52	Thermal Insulation
Soil	General Aggregate[1]	16.61 m^3	37206.04	For roof deck
Timber	Laminated veneer lumber	3.52 m^3	2816	For doors
Glass	Toughened glass	1.06 m^3	2650	For windows
Aluminium	General Aluminium	1.79 m^3	4833	Windows framing and doors
Carpet	Wool	105.86 m^2	253.11	For flooring
Stone	Granite	426.72 m^2	7373.72	Building facade Stone Finish
Paint	General paint	3331.93 m^2	337.88	For internal and external walls
Plastics	PVC Pipe	1736.70 m	2417.97	For plumbing and electrical pipes
Ceramic	General ceramic	-	8499	For floors, walls and skirting tiles
Stone	Marble tiles	-	13344	For floors, walls and skirting tiles

[6] Density of the materials extracted from (Asif, 2017; CIBSE, 2018), to calculate with kg.

2.2.1. Stage 1: Materials selection

This stage covers the *'cradle-to-gate'* assessment[7] for the selected materials, namely "Embodied kgCO_2", "Embodied kgCO_2e", "Embodied energy (MJ)[8]" and "Embodied energy (kWh)". The user will make the selections, as explained below.

2.2.1.1. Step 1: Add details about the construction materials used

A. From the drop-down list, select the material, as shown in Figure 2. For the case study, the first selected material is "Ready Mix Concrete".

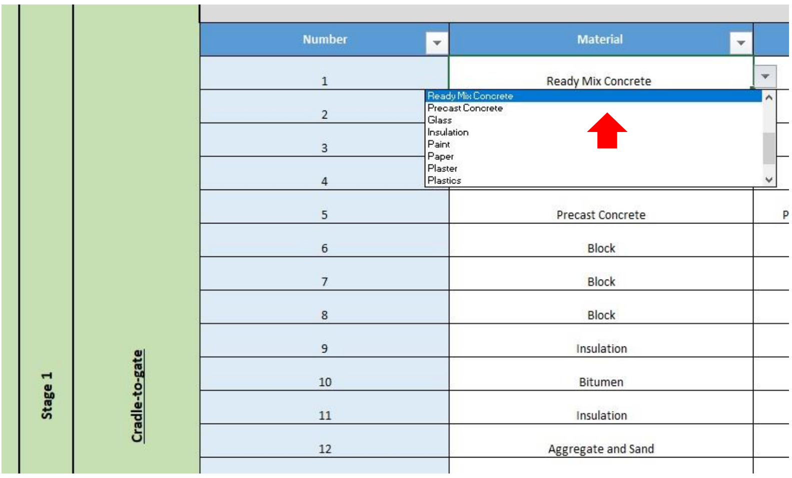

Figure 2: Material selection (Stage 1, Step 1)

B. From the drop-down list, select the type, as shown in Figure 3. The type selected here is "RC (25-30 MPa) - 100% Portland cement (CEM I) ".

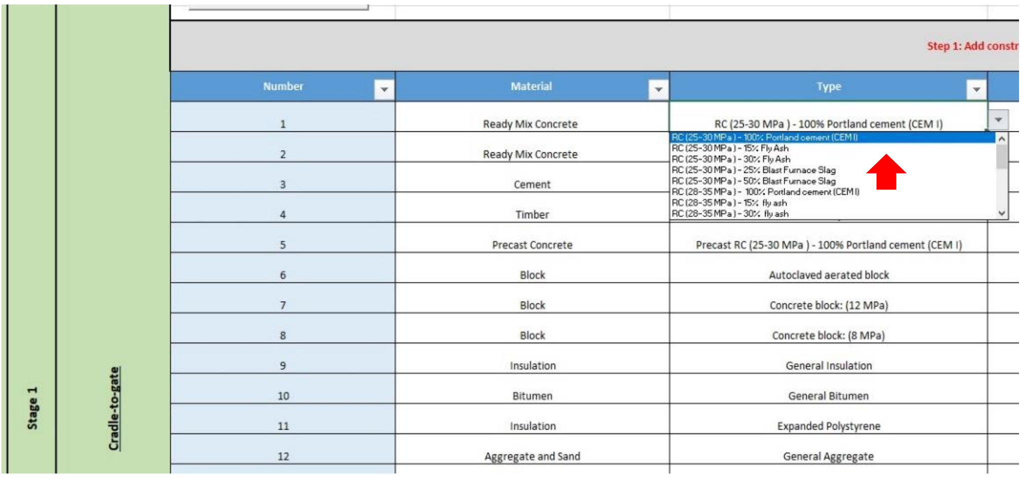

Figure 3: Type selection (Stage 1, Step 1)

[7] The basic data were obtained from (Hammond and Jones, 2011).
[8] 1 MJ = 0.2778 kWh

C. Write the purpose of the selection (i.e. plain concrete, reinforced concrete, steel rebar for concrete structure). Then, enter the quantity of the material type based on the units of measurement[9], as shown in Figure 4. For this example, “76083.7 (Kg)” is entered for “RC (25-30 MPa) - 100% Portland cement (CEM I) ”.

Purpose	Unit	Quantity
Plain concrete for blinding (below foundations , ground beams)	kg	76083.7
Reinforced concrete for foundations, beams, columns, slabs, stairs.	kg	1870151.8

Figure 4: Quantity of material type (Stage 1, Step 1)

2.2.1.2. Step 2: Select whether “Ready Mix Concrete” or “Precast Concrete” is used

A. If either of the above-mentioned materials has been selected, you may need to add details about the quantity of steel reinforcement (kg/m³) adopted therein, as shown in Figure 5. For this case study, “0 kg of steel rebar (for every 1 m^3 of concrete) is entered[10].

Step 2: If “Ready Mix Concrete” or “Precast Concrete” is selected, add details about the quantity of steel reinforcement (kg/m³).	
Additional materials	**Quantity (kg steel rebar/m³ concrete)**
Reinforcement steel - ready mix concrete	0
Reinforcement steel - ready mix concrete	49.05

Figure 5: Steel reinforcement for concrete or precast concrete (Stage 1 – Step 2)

[9] As the unit for the quantity will appear automatically, it does not need to be entered manually.
[10] N.B. The user needs to skip this step if the construction does not include either “Ready Mix Concrete” or “Precast Concrete”; in which case the screen will show “none”.

B. For each "selected material type", the results ("Embodied kgCO_2", "Embodied kgCO_2e", "Embodied energy (MJ)" and "Embodied energy (kWh)") will be automatically calculated in the same row, as shown in Figure 6. The application also provides the total for each of the selected materials in the "last row" of the table. . For the case study, the embodied kgCO_2 for the selected material type "RC (25-30 MPa) - 100% Portland cement (CEM I)" is "9966.96". The other individual results are also reported in the column. The total embodied kgCO_2 for all the materials is shown in the bottom row as "572749.71". Embodied energy (MJ and kWh) are also considered.

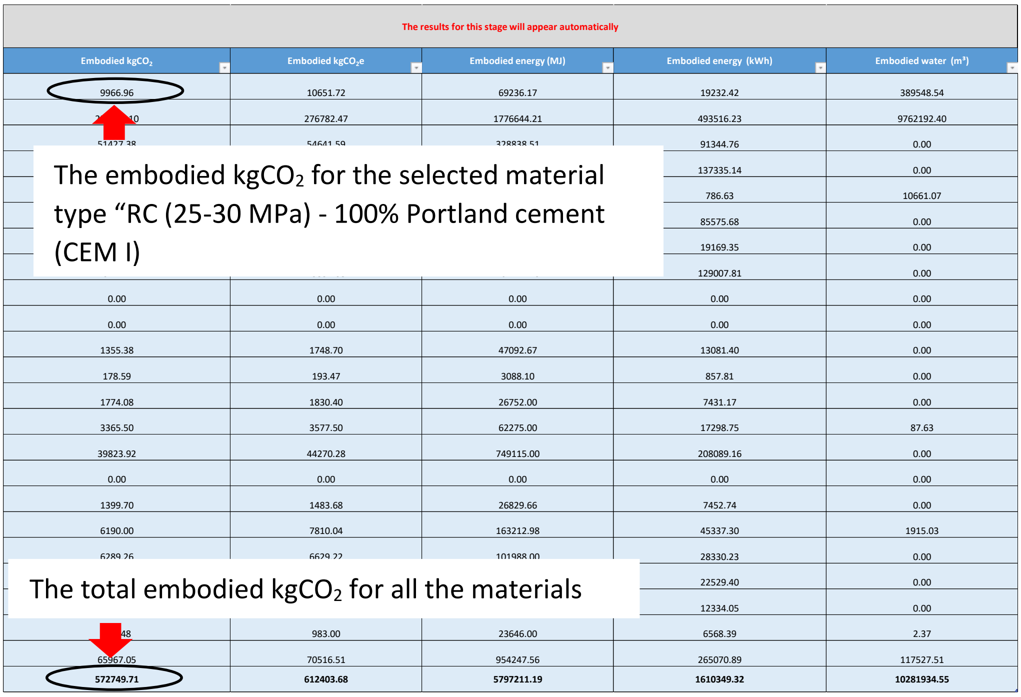

Figure 6: Summary of the results (Stage 1)

C. If you need to add more materials, use the option "Add material", as shown in Figure 7, and an extra row will appear. There is no limit on how many materials you can add. Fifteen materials are added for this case study (e.g. Ready-Mix Concrete through to Blocks).

Figure 7: Addition of other materials (Stage 1)

2.2.2. Stage 2: Transport selections from the gate to the grave.

In order to improve the embodied carbon kgCO_2e outcome for the construction materials, stage 2 has been added to the framework. This stage covers the embodied kgCO_2e associated with transport activities from the gate to the grave. In stage 2, the required details of the relevant construction materials will appear automatically (within the blue cells). The quantities of all the fifteen materials selected for the case study appear as shown in Figure 8. The user will need to input transportation information (See 2.2.2.1)

These details will appear automatically based on previews adding construction material details			
Number	Material	Type	Quantity (tonne)
1	Ready Mix Concrete	RC (25-30 MPa) - 100% Portland cement (CEM I)	76.0837
2	Ready Mix Concrete	RC (28-35 MPa) - 100% Portland cement (CEM I)	1870.1518
3	Cement	Mortar (1:3 cement:sand mix)	247.247
4	Timber	Timber: Plywood	32.96017
5	Precast Concrete	Precast RC (25-30 MPa) - 100% Portland cement (CEM I)	2.08224
6	Block	Autoclaved aerated block	88.02
7	Block	Concrete block: (12 MPa)	95.846
8	Block	Concrete block: (8 MPa)	787.16
9	Insulation	General Insulation	0
10	Bitumen	General Bitumen	0
11	Insulation	Expanded Polystyrene	0.53152

Figure 8: Relevant construction materials (Stage 2)

2.2.2.1. Add transport (activity, type and distance)

A. From the drop-down list, select the category of activity[11] [12], as shown in Figure 9. You may add up to three modes of transport. For the case study, "HGV Diesel" is selected for the category "Activity 1" for the "Ready Mix Concrete".

Activity 1	Type 1	Distance 1 - (km)
HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	14
HGV Diesel Vans Diesel Vans Petrol Rail Freight flights Cargo ship	Rigid (>7.5 tonnes-17 tonnes)	14
	Rigid (>7.5 tonnes-17 tonnes)	139
HGV Diesel	Rigid (>17 tonnes)	14
HGV Diesel	Rigid (>17 tonnes)	18.6

Figure 9: Category of activity (Stage 2, Step 1)

B. From the drop-down list, select the type of activity and add the distance (km), as shown in Figure 10. For the "Ready Mix Concrete", "Rigid (>7.5 tonnes-17 tonnes)" is selected as the type of activity, and the distance is "14 (km)".

Activity 1	Type 1	Distance 1 - (km)
HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	14
HGV Diesel	Rigid (>3.5 - 7.5 tonnes) Rigid (>7.5 tonnes-17 tonnes) Rigid (>17 tonnes) Articulated (>3.5 - 33t) Articulated (>33t)	14
HGV Diesel		139
HGV Diesel	Rigid (>17 tonnes)	14
HGV Diesel	Rigid (>17 tonnes)	18.6

Figure 10: Type of activity (Stage 2, Step 1)

[11] Note that this information should cover transport from (the gate to the grave), and should be completed based on the available information. The processes seen in Figure 9 and 10 will be repeated up to three times.

[12] The "gate" refers to the gate of the factory and the "grave" denotes the end of the life of the material (i.e. after the demolition of the building).

C. The results[13] for each 'selected material' will be automatically calculated in the rows shown in Figure 11. The application will also provide the total for all the selected materials at the end of the table in the "last row". The result considers "Freighting goods (downstream)"[14] , "Well-to-tank (WTT) (upstream)" [15] and "Freighting goods (upstream and downstream)", all of which are included in the value of $kgCO_2e$.

D. As shown in Figure 11 , for the example "Ready Mix Concrete" (first row), the results are:
   - Freighting goods (downstream): 1063.41 embodied $kgCO_2e$
   - Well-to-tank (WTT) (upstream): 253.09 embodied $kgCO_2e$
   - Freighting goods (upstream and downstream): 1316.51 embodied $kgCO_2e$

   Moreover, the total for all the materials (last row) is as follows:
   - Freighting goods (downstream): 60815.95 embodied $kgCO_2e$
   - Well-to-tank (WTT) (upstream): 14301.96 embodied $kgCO_2e$
   - Freighting goods (upstream and downstream): 75117.91 embodied $kgCO_2e$

The results for this stage will appear automatically

Embodied kgCO2e = Freighting goods (downstream)	Embodied kgCO2e = Well-to-tank (WTT) (upstream)	Embodied kgCO2e = Freighting goods (upstream and downstream)
1063.41	253.09	1316.51
26138.92	6221.10	32360.02
14523.14	[illegible]	17978.17
378.16	[illegible]	468.19
25.61	[illegible]	31.70
1082.46	257.71	1340.17
1178.71	280.62	1459.33
9680.43	2304.68	11985.12
0.00	0.00	0.00
0.00	0.00	0.00
9.71	2.31	12.02
1013.83	241.37	1255.20
39.36	9.37	48.73
62.66	14.91	77.57
76.25	18.16	94.41
0.00	0.00	0.00
21.11	5.10	26.21
33.80	8.04	41.84
1328.29	[illegible]	1594.39
1152.34	[illegible]	1383.20
2083.94	[illegible]	2501.43
27.35	6.58	33.93
896.45	213.31	1109.76
60815.95	**14301.96**	**75117.91**

The total embodied $kgCO_2e$ for all the materials

The total embodied $kgCO_2e$ for all the materials

Figure 11: Summary of the results (Stage 2)

[13] Data for freighting goods (downstream) and Well-to-tank (WTT) in "kg CO2e/tonne.km" for mode of transport (i.e. types of activities) were obtained from the Department for Business, Energy & Industrial Strategy, (2018b).

[14] Freighting goods (downstream) reports data are associated with fuels used to operate (power) downstream transport modes.

[15] *"(WTT) to report the upstream emissions associated with extraction, refining and transportation of the raw fuels before they are used to power the transport mode",* as per the Department for Business, Energy & Industrial Strategy (2018b).

2.2.3. Stage 3: U-value calculations for the domestic building

The framework considers U-value calculations to reduce the energy demand in this residential buildings. Annual consumption (energy demand) is calculated for cooling and heating loads as well as embodied kgCO_2 from cooling and heating the building.

2.2.3.1. U-value for "Walls and Roofs"

A. *Step 1: From the drop-down list, select the section type.*

For the case study, section type "roof" is selected for Construction Section 1 and 2, as shown in Figure 12, Wall is selected for Construction Section 3 and 4.

B. *Step 2: Add the area for this selection*

For the case study, the total area of the roof (Number 1) is 175 m^2, as shown in Figure 12.

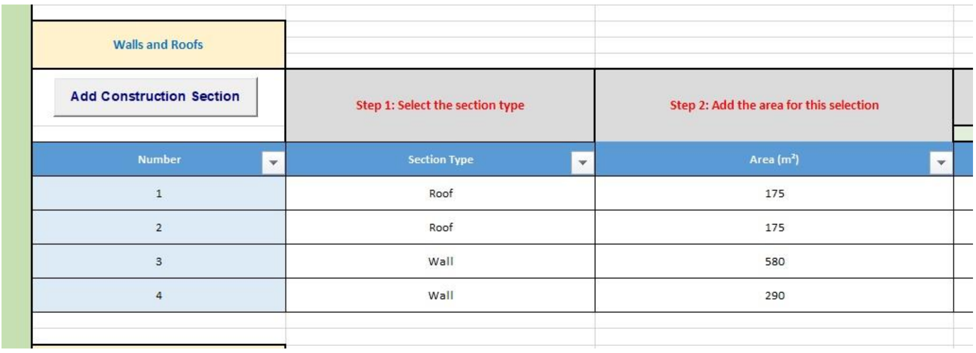

Figure 12: Section type and area (Stage 3: walls and roofs)

C. *Step 3: Add details about section layers. You may add up to six layers (in addition to the outside and inside layers[16])*

- From the drop-down list, select the material category, as shown in Figure 13. For "Layer 1 "of the roof (Material -1), the material category is selected as "Ceramic".

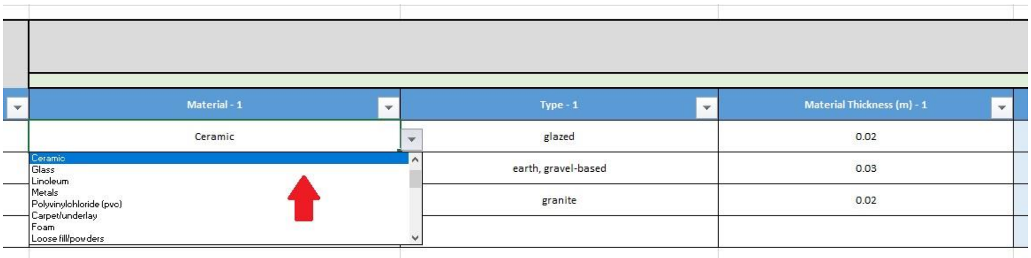

Figure 13: Material category (Stage 3: walls and roofs)

[16] It is assumed that the internal thermal resistance is 0.13 and the external thermal resistance is 0.04 (both values in m^2. K/W).These numbers were sourced from Everett (2016).

-As shown in Figure 14, from the drop-down list, select the material type and then enter details about the material thickness. For "Layer 1 "of the roof, material type is "glazed" and the thickness is "0.02 (m)".

Figure 14: Material type and thickness (Stage 3: wall and roof)

-Regarding the selection of the material and its type, the specifications "Condition/test (where known)", "Source" , "Density (kg/m³)", "Specific heat capacity (J/kg·K)" and "Thermal conductivity (W/m K)" will appear, as shown in Figure 15 (this will help you to make decisions about the choices[17]). For "Layer 1 "of the roof, the properties are as follows: Density "2500 (kg/m³)", Specific heat capacity "840 (J/kg·K)", Thermal conductivity "1.4 (W/m K)", source "CIBSE, UK" and no condition/test where known.

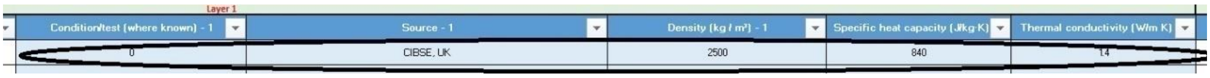

Figure 15: Material specifications (Stage 3: walls and roofs)

- The results[18] for each "construction section" will be automatically calculated, as shown in Figure 16. For the case study, after all the layers are added, the roof resistance (R-value) is "1.06 (m² K/ W)", its conductance (U-Value = 1/R) is "0.95 (W/ m² K)" and its contribution to the gain or loss coefficient is "165.57 (W K^{-1})".

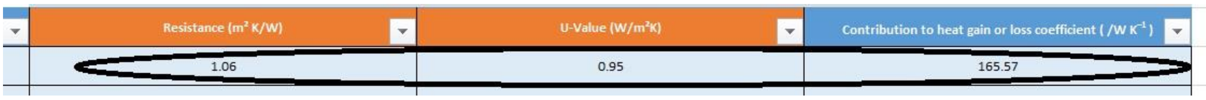

Figure 16: Summary of the results (Stage 3: walls and roofs)

- Note: If you prefer to add more construction sections, use the option "Add Construction Section" as shown in Figure 17, and an extra row will appear. There is no limit to how many construction sections you can add. For the case study includes two types of walls ("external wall") and two types of roofs.

[17] It is recommended that you visit the page "Data 2" in the application to check all details about the materials. You may find the same "material type" with different specifications (e.g. "general 1" and "general 2" in "Asphalt". On the page "Data 2" also, you will find the table for the codes and source references. The basic data were obtained from CIBSE (2018).
[18] The contribution to the gain or loss coefficient (W K^{-1}) is calculated using multiple U-values (W/m² K) and the area (m²). This formula is common for the construction section, glazing, and ground floors. This formula were sourced from Everett (2016).

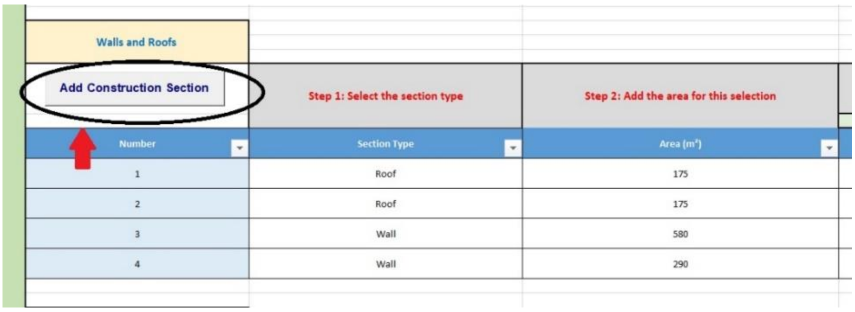

Figure 17: Add construction section (Stage 3: walls and roofs)

2.2.3.2. U-value for "Glazing"

A. *Step 1: Select the glazing properties*[19].

- From the drop-down list, select the type of frames, as shown in figure 18. For the case study, the type of frames is "metal frames 8mm thermal break ".

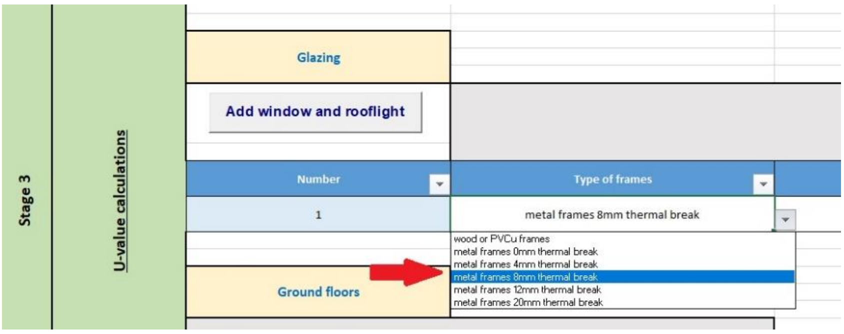

Figure 18: Type of frames (Stage 3: glazing)

- From the drop-down list, select the type of glazing, as shown in Figure 19. In the case study, "Double glazing (low-E, εn = 0.1, air filled)" is selected as the type of glazing.

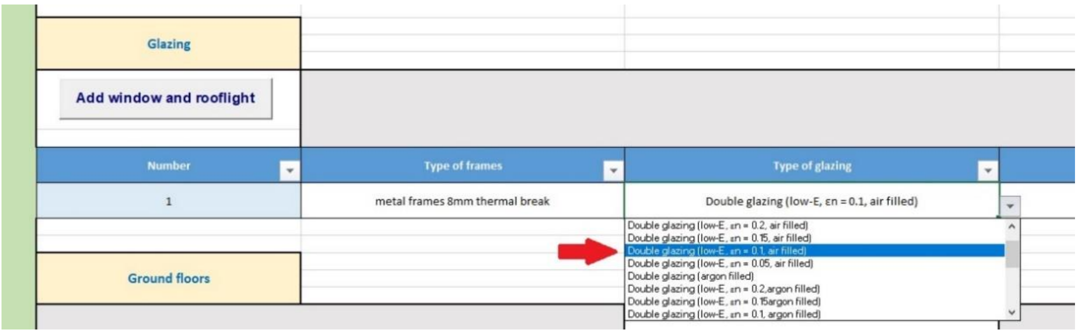

Figure 19: Type of glazing (Stage 3 – glazing)

[19] For the glazing, select the properties "types of frames, glazing, gap between panes and conditions". Then the result for the U-value will appear based on the criteria tables sourced from CIBSE (2018).

- From the drop-down list, select the gap between the panes[20], as shown in Figure 20. For the case study, the gap between the panes is “12mm “.

Figure 20: Gap between the panes (Stage 3: glazing)

- From the drop-down list, select the conditions (window or rooflight”, as shown in Figure 21.For the case study, the selection is “window”.

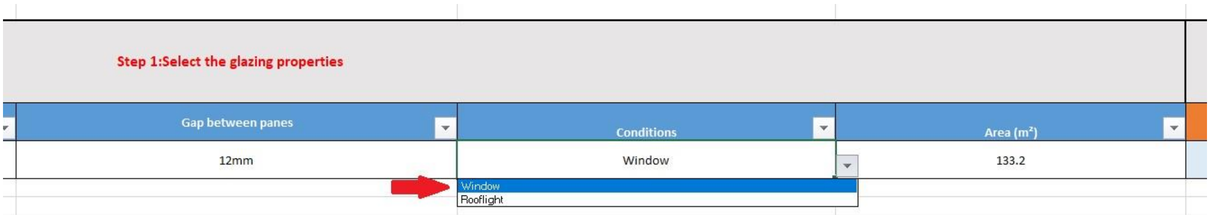

Figure 21: Conditions for window or rooflight (Stage 3 – glazing)

- Enter the Area (m²), as shown in the Figure 22; when you enter the area, count the total area of this selection. For the case study, the area for the selection is “133.2 (m²)”.

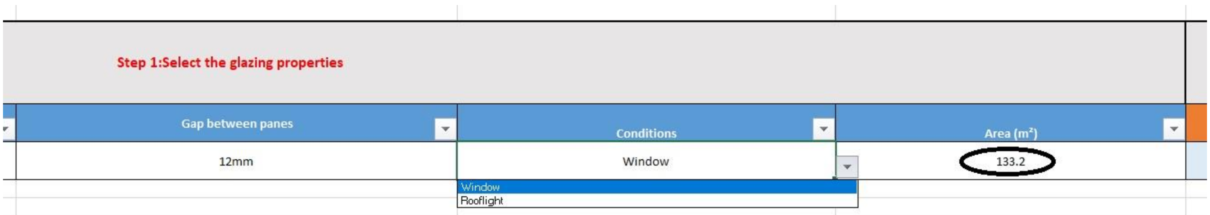

Figure 22: Area for window or rooflight (Stage 3: glazing)

- If you prefer to add more windows or rooflight types, use the option “Add window or rooflight”, as shown in Figure 23, and an extra row will appear. There is no limit to how many times you can use this option. For the case study has only one type of window.

Figure 23: Add window or rooflight (Stage 3 – glazing)

[20] Select “not applicable“ when the selection is single-glazed. You cannot select “not applicable “when the selection is double- or triple-glazed.

B. For each “selected window or rooflight types”, the results will be automatically calculated, as shown in Figure 24.

- For the first type, the U-value is “2.5 (W/m^2.K)” and the contribution to the gain or loss coefficient is “333 (W K^{-1})”.

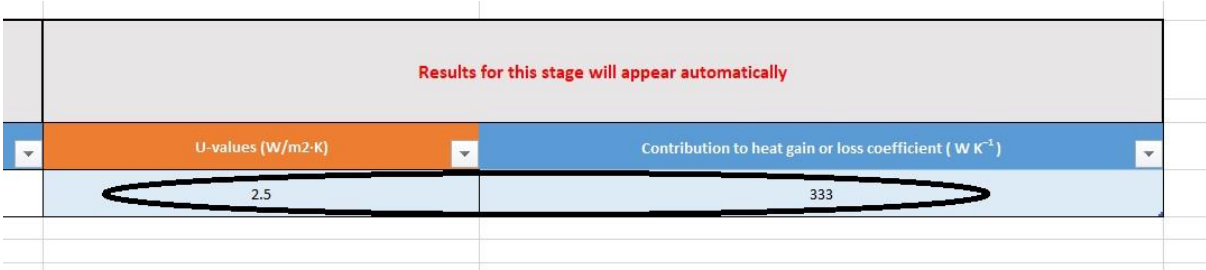

Figure 24: Summary of the results (Stage 3: glazing)

2.2.3.3. U-value for “Ground floor”

A. *Step 1: Enter the ground floor area and perimeter*, as shown in Figure 25. For the case study, ground floor area is “381 (m^2)” and the perimeter is “95 (m)”.

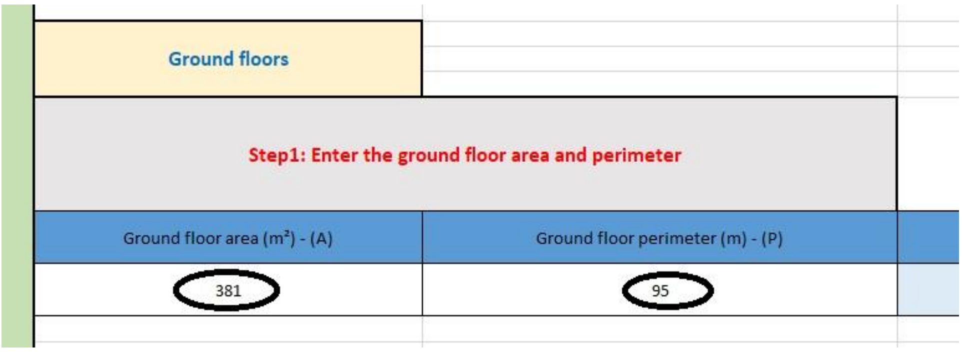

Figure 25: Ground floor area and perimeter (Stage 3: Ground floor)

B. Step 2: Select the soil type from the drop-down list, as shown in Figure 26. For the case study, the soil type is “Sand or gravel”.

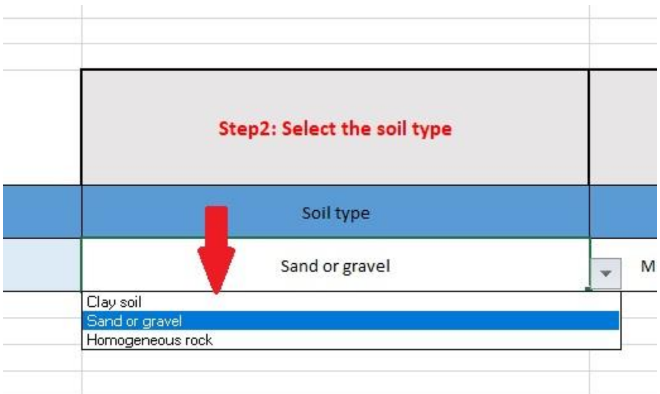

Figure 26: Soil type (Stage 3: Ground floor)

C. ***Step 3: Select the insulation type from the drop-down list. Then, enter the thickness of the insulation material, as shown in Figure 27.For the case study, “polyurethane, expanded)” insulation of “0.01 (m)” thickness is selected.***

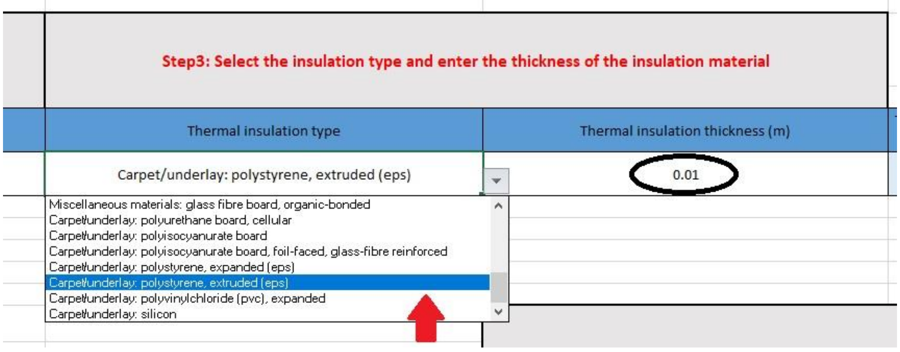

Figure 27: Insulation type and thickness

The results[21] for the selection “Ground floor” will be automatically calculated, as shown in Figure 28. For the first type, the U-value is “0.41 (W/m^2.K)” and the contribution to the gain or loss coefficient is “156.21 (W K^{-1})”.

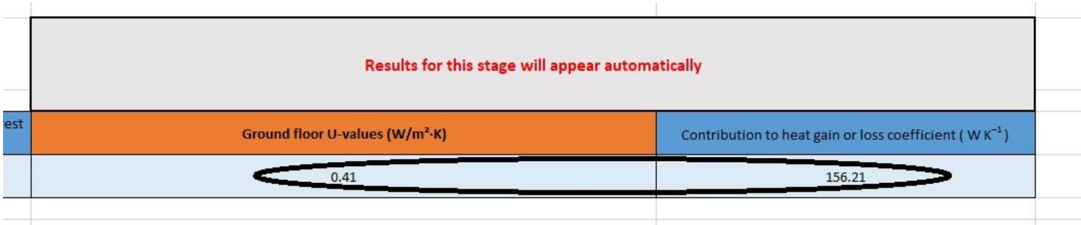

Figure 28: Summary of the results (Stage 3: Ground floor)

2.2.3.4. Annual consumption (energy demand) for cooling or heating load

This section will provide an overview of annual consumption (energy demand) which will reflect the following previous selections: “Wall and Roofs”, “Glazing” and “Ground floor”[22] .In addition, it will reflect “house ventilation” and “cooling and heating degree“ which will be presented for selection at this stage.

A. ***Step 1: Select a city* from the drop-down list, as shown in Figure 29. For the case study, Dammam city is selected as the location.**

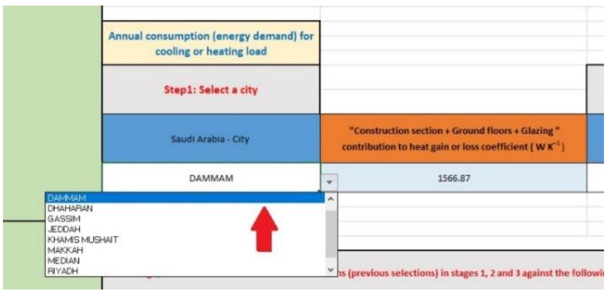

Figure 29: Location (city) (for calculation of annual energy demand)

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[21] The result of the U-value will appear based on criteria tables sourced from CIBSE (2018).

[22] Figure 29 shows the total contribution to the heat gain or loss coefficient of a house (W K^{-1}) which is calculated from the sum “Construction section + Ground floors + Glazing” in the previous sections.

B. *Step 2: Enter the volume of the house from the drop-down list, as shown in Figure 30.*

Figure 31, provides the contribution of ventilation to the heat gain or loss coefficient (W K^{-1})[23]. For the case study, the house volume is “3735 (m^3)” and the contribution of ventilation to the heat gain or loss coefficient is “431.39 (W K^{-1}) “.

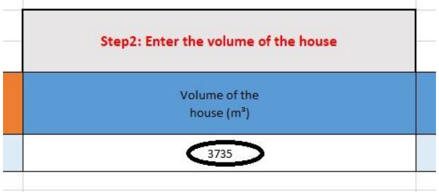

Figure 30: Volume of the house (for calculation of annual energy demand)

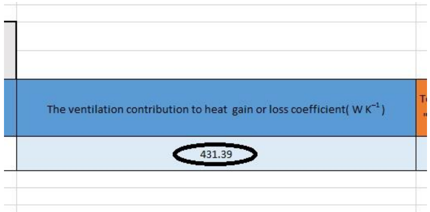

Figure 31: Contribution of ventilation to heat gain or loss coefficient

C. *The results of the annual energy demand of the house will be automatically calculated, as shown in Figure 32. The results include the annual consumption “energy demand (kWh)”[24,25,26] for the cooling and heating loads and the annual “embodied (kgCO_2e)” which is derived from energy consumption.*

For the case study shown in Figure 32, the following are the results of annual energy demand for the house:

- Annual consumption - Energy demand for cooling load (kWh): 166080
- Annual consumption - Energy demand for heating load (kWh): 10215
- Annual consumption - Energy demand (kWh) for cooling and heating load: 176295
- Annual consumption - Embodied (kgCO_2e) for cooling load: 113765
- Annual consumption - Embodied (kgCO_2e) for heating load: 6997
- Annual consumption - Embodied (kgCO_2e) for cooling and heating load: 120762

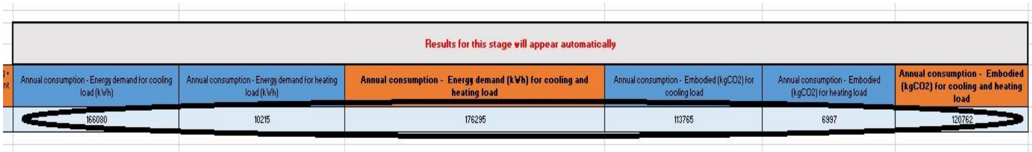

Figure 32: Summary of the results (for calculation of annual energy demand)

[23] The contribution of ventilation to the heat gain or loss coefficient (W K^{-1}) is calculated as $0.33 \times V \times n$, where V is the volume of the house, and n is the air change rate per hour (ACH), which assumed to be 0.50 (for an airtight construction). This formula was sourced from Everett (2016).

[24] Energy demand (kWh) = Total contribution to the heat gain or loss coefficient of a house (W K^{-1}) * degree days × (24 / 1000). This formula was sourced from Everett (2016).

[25] The multiplication by 24 is necessary to convert days into hours (Everett, 2016).

[26] The data on degree days were extracted from ASHRAE (2017) depending on the selected city in Saudi Arabia.

2.2.4. Stage 4: Assessing the resilience of possible sustainable solutions in the future

Assessment of the resilience of the sustainable solutions of the previous selections in stages 1, 2 and 3 is conducted against certain aspects. The illustration in Figure 33 (Lombardi et al., 2012) serves as a guide to complete the tables shown in Figures 34 and 35.). In the framework, three domains are considered – a new sustainable paradigm, policy reform and market forces – regardless of whether or not conditions in the future are likely to change.

That is why stage 4 has been developed, to understand whether the proposed solutions can be implemented, and whether they will function and cope with changes in the future. Even if research a framework is successfully developed to assess the sustainability performance of buildings, there will undoubtedly be further questions raised that will necessitate further research so that the framework can be enhanced, corrected and evolved (Marjaba and Chidiac, 2016). It is fair to say that the engineering and construction community needs to work much harder to ensure the promotion of sustainability in work practices. If the levels of sustainability are to keep improving in the future, assessment and continuous improvement are essential (Bakhoum and Brown, 2012).

STEP 3: DETERMINE THE PERFORMANCE OF THE NECESSARY CONDITIONS IN THE FUTURE

Local sourcing of construction materials to reduce carbon footprint

Necessary conditions	New Sustainability Paradigm	Policy Reform	Market Forces	Fortress World
Incentives (financial and non-financial) to encourage local sourcing	Local sourcing is encouraged and supported by social and environmental policy and values. Support mechanisms are in place to encourage local sourcing	Increasing environmental concerns drive policy towards more local sourcing of products and materials used in construction	Profit making is at the core of business activities. Local supplier decision is driven by cost. Desirable if local products' high quality enable high value for the developers	For the poor, environmental concerns are secondary. The rich may choose to source locally if it is perceived to address their resource and security concerns
Consumers support local sourcing	The local population recognises environmental responsibilities and supports local products	Some consumers ignore policy guidelines. Behavioural change is slow and uptake of locally sourced products may take time	Consumers prefer global brands with international reputation. However, local materials inevitably become cheaper because of increasing transport prices	The poor have no choice but to opt for whichever products are available. The rich may choose to source locally if it is perceived to address their resource and security concerns
Materials are available locally	Environmental priority means reclaimed materials in particular are managed judiciously	Policy drives market for local materials, but global markets compete with local markets	Materials flow to regions with specialised infrastructure. National construction companies may not operate at regional/ local level – instead all sourcing is done nationally	Rich control resources, so materials are available. Poor are accustomed to working with local materials
Local storage space for reclaimed materials	Use of reclaimed materials is consistent with sustainability priorities, so local storage space is made available	Policy requires provision of storage for reclaimed materials	Where market prices support reclaimed materials, infrastructure (including storage) is in place	Rich prioritise control of critical resources, so have local storage space. Poor have no choice but to store and use reclaimed materials
Efficient local handling and transport systems	Use of reclaimed materials is consistent with sustainability priorities, so local handling and transport are made available	Policy requires provision of local handling and transport systems but cannot dictate their efficiency	Where market prices support reclaimed materials, infrastructure (including storage) is in place	Rich prioritise control of critical resources, so have local handling and transport. Poor have no choice but to use reclaimed materials

Key: ■ condition highly unlikely to continue in the future
■ condition is at risk in the future
■ condition highly likely to continue in the future

Figure 33: Example of assessing the resilience of possible sustainable solutions in the future (adapted from Lombardi DR et al. (2012))

For the case study, the following forms will be filled[27], as shown in Table 3.

Table 3: Assessing the resilience of possible sustainable solutions in the future for the case study

Aspects	Necessary conditions	New sustainability paradigm	Policy reform	Market forces
The local sourcing of materials	Materials are available locally	The availability of materials should be promoted by government regulations by setting direct sustainable environmental standards for materials, and manufacturers or providers should work on this basis.	Regulations which meet sustainable environmental standards to be developed for future implementation, setting a maximum amount of embodied carbon or energy.	New regulations might be challenged by industry, and this could make it difficult for them to achieve their aims. It is strongly suggested that the construction industry implement these rules gradually rather than with immediate effect.
	Government policy to encourage use of sustainable materials	Establishing a sustainable code in Saudi Arabia considering the concerns facing the construction industry with respect to sustainable construction	As of yet, no such policy exists for encouraging the engineering community to take steps towards sustainable solutions. A Saudi Green Building Code is under development, and the hope is that this code will facilitate a step towards sustainability. There is a need for sustainable domestic buildings.	Sustainability knowledge in the engineering and construction community is a matter of concern.
The long-term 'bounce-back-ability' of the buildings	The ability of materials or buildings to withstand weather conditions (e.g., sandstorms, floods, extreme ranges and values of heat/cold)	A call to utilise construction materials which can withstand weather conditions is an important factor which needs to be in place in terms of regulations.	Adapt or enforce regulations which fully encompass the weather conditions in the region	Construction materials should be carefully selected. There might also be an issue with the construction process in terms of supervision.
	The maintenance and long-term operation of the building	Reducing operation costs and ongoing maintenance efforts	Industry to be a partner in promoting this solution for the public and their own business	Business cooperation and how this step may progress, thinking about profits or providing a higher level of services
	Preparation for expected or unexpected circumstances	Government organisations or community to be made aware or educated about future certainties and uncertainties	Government organisations to establish studies to identify these further circumstances.	Government organisations to carefully assess the benefits of establishing these studies.
	Social or economic effects	It is unclear how the public will accept these changes, especially when it comes to the economic element, which is perhaps the most important to them.	Openly said, final and initial construction costs are major drivers for any changes in the selected materials. Looking at the long-term costs of energy consumption might help to change people's behaviour to select sustainable materials.	Engineering and construction community could suggest low prices and higher benefits for sustainable materials. The problem with that option is that the engineering and construction community might want to increase profits without giving back to the community.

[27] Light green: condition highly likely to continue in future, Light Orange: condition is at risk in future, and Orange: condition highly unlikely to continue in future.

Part 2

(Beta version)

3. Part 2: Results (output):

A summary of the results will appear as graphs and tables, as shown in Figures 36 and 37.

- Note: You can retune the "input" to change the materials in order to improve the results and identify materials with lower embodied energy and embodied carbon.

- For the case study, the total embodied $kgCO_2e$ for "Ready Mix Concrete" was highest among all the materials. Moreover, Figure 36 reports details for both "cradle to gate" in blue and transportation (gate to crave) in orange.

The framework can provide additional details, there are seven figures present the results.

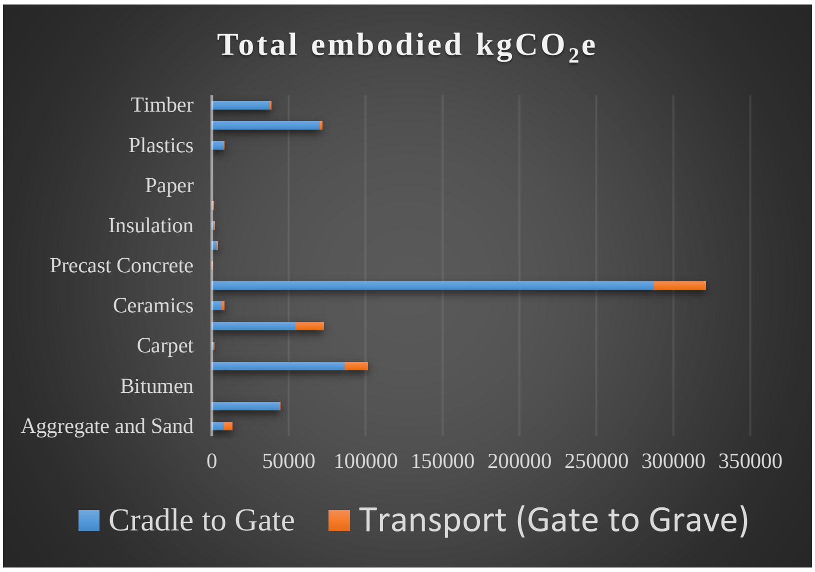

Figure 34: Example of final results (figures)

- For the case study, the table in Figure 37 presents the total embodied $kgCO_2e$ for all the materials: approximately 612403.68 $kgCO_2e$ for cradle to gate and 75117. $kgCO_2e$ for transportation (gate to grave). Refer to the framework for additional details of the results.

Summary tables

Material	Embodied kgCO2e	
	Cradle to Gate	Transport (Gate to Grave)
Aggregate and Sand	8154.85	5139.82
Aluminium	44270.28	94.41
Bitumen	0.00	0.00
Block	86715.65	14784.62
Carpet	1483.68	26.21
Cement	54641.59	17978.17
Ceramics	6629.22	1594.39
Ready Mix Concrete	287434.18	33676.53
Precast Concrete	351.90	31.70
Glass	3577.50	77.57
Insulation	1748.70	12.02
Paint	983.00	33.93
Paper	0.00	0.00
Plaster	0.00	0.00
Plastics	7810.04	41.84
Steel	70516.51	1109.76
Timber	38086.59	516.92
Total	612403.68	75117.91

Figure 35: Example of final results (tables)

- For the case study, Table 3 demonstrates the extent of the savings in embodied carbon or energy for 76,083.7 kg of (25-30 MPa) ready mix concrete and 1,870,151.8 kg (28-35 MPa) ready mix concrete. The saving might lead to 40.60% reduction in the emissions level, and energy consumption may be reduced by 27.41%, when substituting cement.

Table 4: The influence of blast furnace slag or fly ash replacement on embodied carbon $kgCO_2e$ and embodied energy (MJ) of ready mix concrete

Material	Type	Embodied $kgCO_2e$	Total saving (%)	Embodied energy (MJ)	Total saving (%)
Ready Mix Concrete	100% Portland cement (CEM I)	287434.18		1845880.38	
Ready Mix Concrete	Replacing cement with 15% fly ash	267971.83	6.77	1747807.77	5.31
Ready Mix Concrete	Replacing cement with 30% fly ash	240648.45	16.28	1592108.93	13.75
Ready Mix Concrete	Replacing cement with 25% blast furnace slag	230993.35	19.64	1611571.28	12.69
Ready Mix Concrete	Replacing cement with 50% blast furnace slag	170736.14	40.60	1339859.15	27.41

- The case study includes three types of blocks: autoclaved aerated blocks, concrete blocks (8 MPa) and concrete blocks (12 MPa). Their use is presented in detail in Table 6. Concrete blocks (12 MPa and 8 MPa) will still be proposed. However, the second action will be to change the selection of autoclaved aerated blocks to concrete blocks (8 MPa). This will result in a significant minimisation of more than 20% of embodied carbon and energy; Table 6 shows the details. The reason behind this reduction is because autoclaved aerated blocks embody 3.50 MJ/kg and 0.326 $kgCO_2e/kg$, compared to 0.59 MJ/kg and 0.063 $kgCO_2e/kg$ for concrete blocks (8 MPa).

Table 5: Comparison of the two proposed options for blocks (concrete products)

	Old proposed option	New proposed option
Blocks (concrete products)	**Autoclaved aerated block: 7335 pieces Concrete block (12 MPa): 2819 pieces and Concrete block (8 MPa): 27226 pieces**	**Concrete block (12 MPa): 2819 pieces and Concrete block (8 MPa): 34561 pieces**
Embodied $kgCO_2e$	86715.65 $kgCO_2e$	67729.73 $kgCO_2e$ (21.89% saving)
Embodied energy (MJ)	841503.52 MJ	624314.17 MJ (25.81% saving)

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Appendix F. User manual (final version)

A Resilience and Environmentally Sustainable Assessment Framework (RESAF) for Domestic Building Materials in Saudi Arabia

An explanation of the functioning of the framework

(Final version)

(Final version)

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(Final version)

1. Introduction

1.1. Background

The impact of construction materials on the environment is the focus of many researchers, whether regarding the materials themselves, known as embodied impacts (Anand and Amor, 2017; Asif et al., 2017), or energy usage during the building's operations (Taleb and Sharples, 2011; Krarti et al., 2020). This is true everywhere in the world, especially in Saudi Arabia, a country that is facing challenges in respect of energy demands in the domestic buildings sector (Al Kanani et al., 2017). Almost 43% of total national electricity demand is consumed by this sector (General Authority for Statistics, 2018). In addition, higher demand for construction materials is a matter of concern in regard to their embodied energy and carbon; this is especially notable for concrete, which is the main material used in the construction of Saudi Arabian domestic buildings (Asif et al., 2017). All these issues need to be dealt with and resolved, with the assurance of the 'future-ability' of any proposed solutions (Lombardi et al., 2012). A successful task is obliged to respect the context and conditions of Saudi Arabia, such as policies, regulations, environmental factors, etc., which mean that the available assessments of sustainability and resilience simply lack meaning or are insufficient (Shaawat and Jamil, 2014; Al-Tamimi, 2017). That is why, in meeting these needs, a newly developed resilience and environmentally sustainable assessment framework (RESAF) is urgently required to fill the gap of other available assessments. The aim of this document is to present:

'*A framework for assessing both the resilience and sustainability of construction materials used in domestic buildings in Saudi Arabia*'.

The Microsoft Excel-based tool that accompanies the framework can be downloaded from the following link (https://drive.google.com/drive/folders/1z3jJOhpl-IJdPYcp5JPUnqZo5cw5eu9G – password: 8090). It was developed to help building practitioners (e.g., architects, designers, builders, engineers, contractors) in Saudi Arabia to select appropriate building materials which meet sustainability (noting that environmental sustainability is the focus) and resilience criteria. The purpose of the environmental sustainability criteria is to reduce carbon emissions and energy usage for both the materials (embodied impacts) and for the long-term cooling and heating of domestic buildings, while the resilience criteria is to ensure that the selected materials (proposal of solutions) are fit for purpose in the future (see Figure 1). Although the developed framework is intended to be used for domestic buildings in Saudi Arabia, it could, with minor adjustments, be used for other types of buildings. Likewise, the generic aspects could allow application to other regions. This document explains the framework functioning and guides its use in the same way as training, with detailed explanations and examples. The first part (the current section) is effectively an induction session prior to using the framework, summarising the purpose of the framework as well as information about requirements. The second part (Section 2) shows how the framework is actually implemented – for example, how to complete the forms – and explains the outcomes, along with tips on how to improve the outcomes. A case study tutorial ensures that potential users fully understand how the case study will be implemented and what is expected (in terms of outcomes) when using the framework. It is strongly advisable to read Chapter 4, Sections 4.2 and 4.3, in the PhD thesis in order to obtain information about the specifics of the data and the calculations and assessment methods underpinning the design of the RESAF.

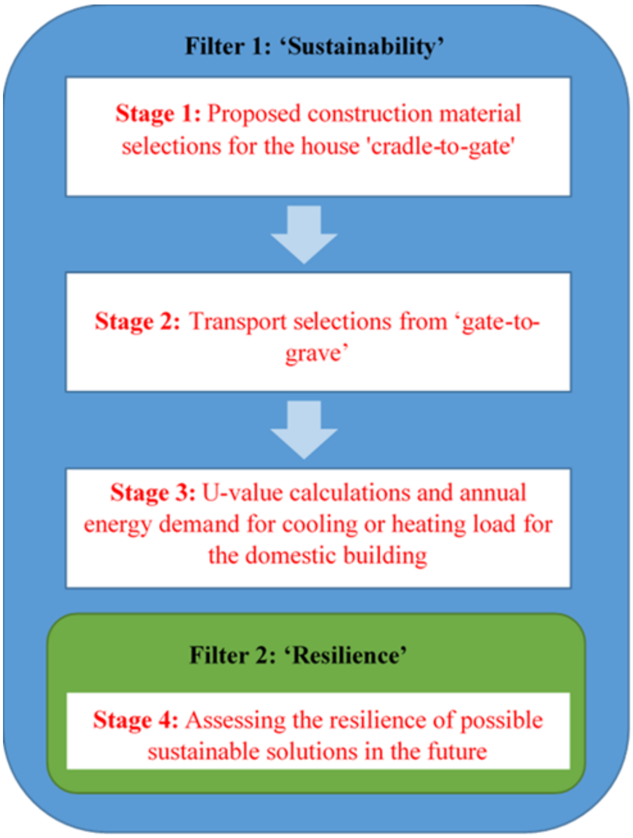

Figure 1: RESAF framework filters and steps

1.2. Framework requirements

Users of the framework must install the following applications on their computer:

1- Microsoft Excel (version 2016 and higher)[1]; and
2- A PDF file reader application (such as Adobe Acrobat).

In order to use this framework as intended, the following information is required in order to make an assessment of the domestic building:

1. Domestic building plans and dimensions;
2. Location of the building;
3. Soil types at the location of the building;
4. Construction materials (types and quantities);
5. Modes of transport and gate-to-grave (from the factory gate to the end of the use of the building) distances (where available).
6. Detailing about wall and roof construction; and
7. Glazing types (e.g. windows or skylights).

Utilising the framework might be possible, even if some of the information listed above is not available. However, in such cases, appropriate assumptions should be

[1] This requirement ensures that the file formats will not change when an older version is used.

made, and suitable justification provided. The accuracy and efficiency of the outcomes (i.e. results) are very much dependent on the availability of the above-mentioned information as well as the choices made by the users while implementing the framework.

2. User manual and tutorial

2.1. General instructions

A. Before using the framework, and as a general rule of thumb, the user should either fill or make selections in the white-coloured cells only; no changes should be made to the light blue-coloured cells. The cells will be filled automatically based on the user's selections. An example of the cells in the form is shown in Figure 2.

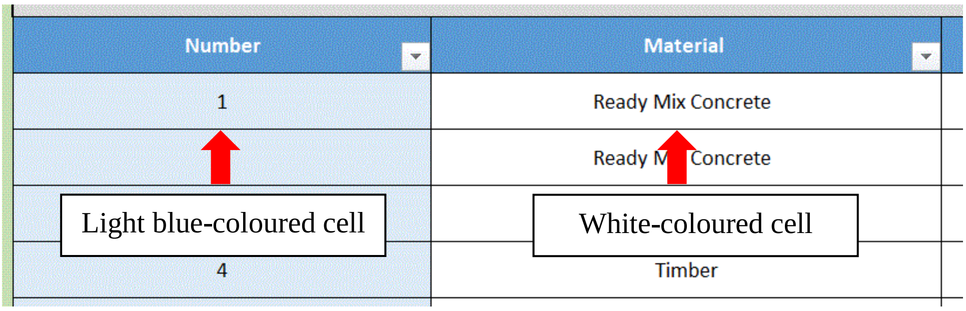

Figure 2: General instructions (colours of the forms)

B. The user must make a series of material selection choices when filling the forms; this will be elucidated through the use of an example. These selections will be based directly on user decisions and will undoubtedly be influenced by the accuracy of the available data for the proposed house (existing or planned). Users always have the option to change their decisions or selections and reverse the calculations (results). This allows the user to undertake multiple runs and look at the environmental and resilience impacts.

C. It is recommended that the user consult the framework (the Microsoft Excel application) at the same time as reading this document so as to facilitate understanding of how the framework should be applied. Moreover, the user will gain more information about the details, decisions, assumptions and results of the example case study.

D. To get the full benefit of the framework and its potential for future development, it is recommended that the user apply their own case study/project.

(Final version)

2.2. Part 1: Information and details about the proposed house building (inputs)

2.2.1. Case study details

The case study project is a design proposal for a house to be built in Dammam, Saudi Arabia, with a total floor area of 890 m^2. Comprising three floors (see Table 1), the concrete structure employs a two-way ribbed slab system. The construction materials are specified in the design proposal, and materials, quantities and specifications are summarised in Tables 2 and 3, in line with the design plans. The total weight of materials is approximately 3,317,715 kg.

Table 1: Proposed house – floors

Floors	Built area (m^2)	Purpose	Plans[1]
Ground	381	Visitors' reception and main kitchen	Figure 3
First	380	Family living	Figure 4
Penthouse	129	Service floor	Figure 5

[1]See Figure 6 for floor heights.

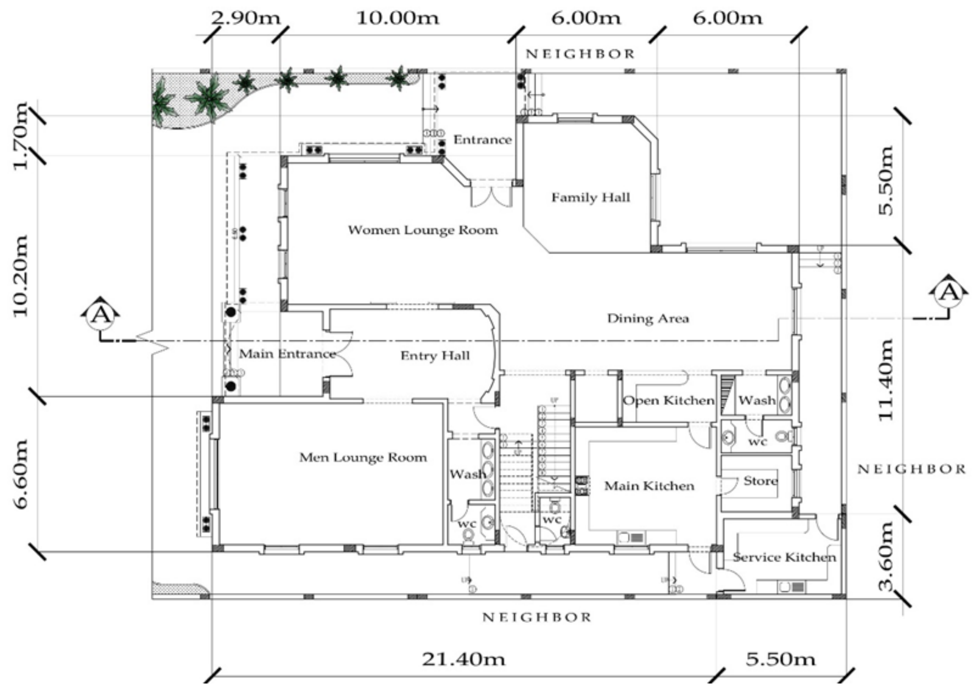

Figure 3: Ground floor plans for the domestic building

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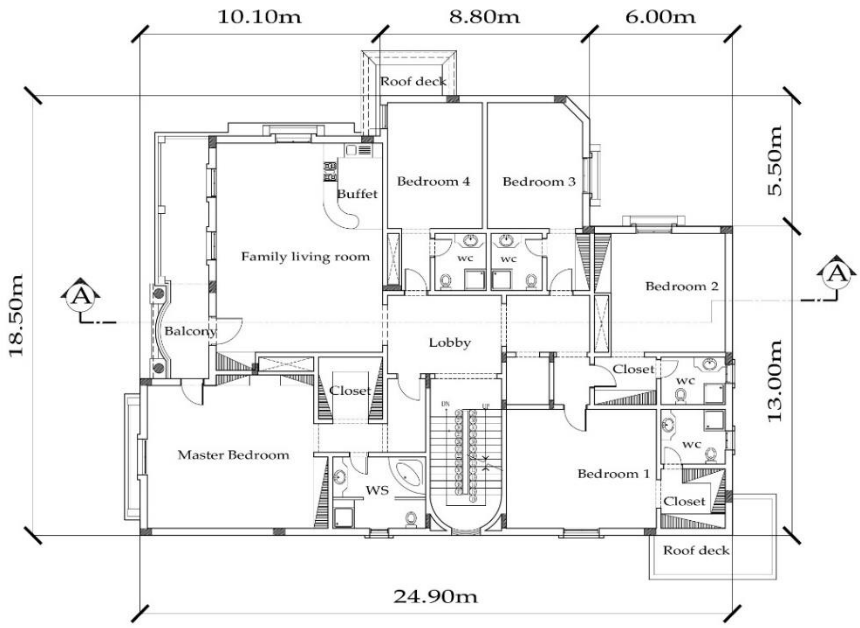

Figure 4: First floor plan

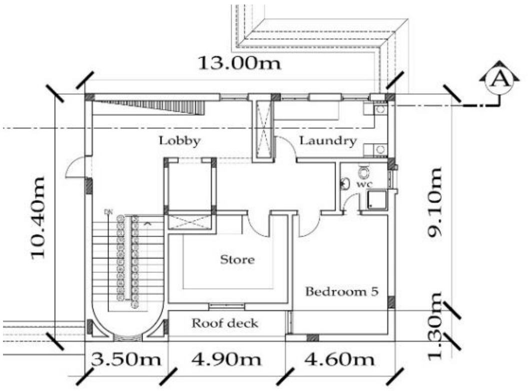

Figure 5: Penthouse floor plan

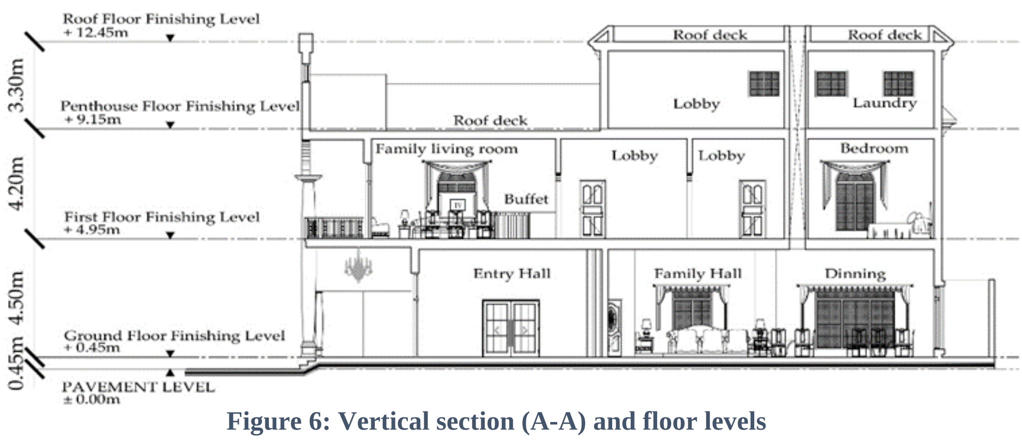

Figure 6: Vertical section (A-A) and floor levels

(Final version)

Table 2: Proposed construction materials in the domestic building design

Material	Type	Quantity (Unit)	Quantity (Kg)	Specifications and purpose
Ready-mix concrete	(25–30 MPa) – 100% Portland cement (CEM I)	31.57 m^3	76,084	Plain concrete for blinding (below foundations, ground beams)
Ready-mix concrete	(28–35 MPa) – 100% Portland cement (CEM I)	772.79 m^3	1,870,152	Reinforced concrete for foundations, beams, columns, slabs, stairs
Cement	Mortar (1:3 cement: sand mix)[1]	130.13 m^3	247,247	Top-of-floor slab to receive finishes, concrete blocks insulation and plastering for exterior and internal walls
Steel	Reinforcement steel[1]	–	37,912	Steel rebar for concrete structure elements
Timber	Plywood[1]	3,923.83 m^2	32,960	Formworks in construction process for concrete structure elements
Precast concrete	(25–30 MPa) – 100% Portland cement (CEM I)	5.76 m^2	2,082	Exterior wall cladding
Block	Autoclaved aerated block	7,335 pieces	88,020	Filling the empty spaces in the two-way ribbed slabs
Block	Concrete block: (12 MPa)	2,819 pieces	95,846	Masonry solid blocks for foundation walls
Block	Concrete block: (8 MPa)	27,226 pieces	787,160	Masonry hollow blocks for external and internal walls
Insulation	Expanded polystyrene[2]	16.61 m^3	531.52	Thermal insulation
Soil[3]	General aggregate[1]	16.61 m^3	37,206	Roof deck
Timber	Laminated veneer lumber[2]	3.52 m^3	2,816	Doors
Glass	Toughened glass[2]	1.06 m^3	2,650	Windows
Aluminium	General aluminium[1,2]	1.79 m^3	4,833	Window framing and doors
Carpet	Wool	105.86 m^2	253	Flooring
Stone[3]	Granite[1]	426.72 m^2	7,373	Building facade stone finish
Paint	General paint[2]	3,331.93 m^2	337	Internal and external walls
Plastics	PVC pipe[1]	1,736.70 m	2,417	Plumbing and electrical pipes
Ceramic	General ceramic[1]	–	8,499	Floors, walls and skirting tiles
Stone[3]	Marble tiles[1]	–	13,344	Floors, walls and skirting tiles
Total	–	–	3,317,715	-

[1,2] Density of the materials extracted from Asif et al. (2017) and CIBSE (2018) to calculate kg.
[3] These materials are categorized under ‘Aggregate and Sand’

Table 3: Properties of elements used in the case study building – base case

Building elements[2]	Details	Area (m^2)
Roof 1	Ceramic (20 mm), polyurethane (0.20 mm), polystyrene 'extruded' (20 mm), bitumen (4 mm), cement mortar '1650 kg/m^3' (10 mm), reinforced concrete (200 mm)	175
Roof 2	Gravel (30 mm), polyurethane (0.20 mm), polystyrene 'extruded' (20 mm), bitumen (4 mm), cement mortar '1650 kg/m^3' (10 mm), reinforced concrete (200 mm)	175
Wall 1	Granite (20 mm), masonry block (200 mm), polystyrene 'extruded' (20 mm), cement mortar '1650 kg/m^3' (10 mm)	580
Wall 2	Masonry block, (200 mm), polystyrene 'extruded' (20 mm), cement mortar '1650 kg/m^3' (20 mm)	290
Window	Double glazing, aluminium frame, air filled, low emissivity: εn = 0.1 'soft coat', 12 mm gap between panes and 8 mm thermal break	133.20
Ground floor	Land soil type is sand or gravel, and polystyrene 'extruded' (20 mm) is used for the insulation.	381

[2] Design assumptions: the base case of the domestic building is designed to have two types of walls and roofs. The Wall 1 type of 580 m^2 is used in the main elevation and in most parts of the building's side elevations. The Wall 2 type of 290 m^2 is used in the back elevation and in the rest of the side elevations. In regard to Roof 1 and 2 (both types covering 175 m^2), the first type with gravel is used near the machines in the roof, while the second type with ceramics is used on the other spaces in the roof.

2.2.2. Stage 1: Materials selection

This stage covers the 'cradle-to-gate' assessment for the selected materials, namely 'embodied kgCO_2e' and 'embodied energy (MJ[3] or kWh)'. The user will make the selections based on the proposed materials (see Table 2) for the domestic building, as explained below (noting that Stage 1 has been calculated based on Section 4.2.1 in the thesis)[4].

2.2.2.1. Step 1: Add details about the construction materials used

A. From the drop-down list, select the material, as shown in Figure 7. For the case study, the first selected material is 'ready-mix concrete'.

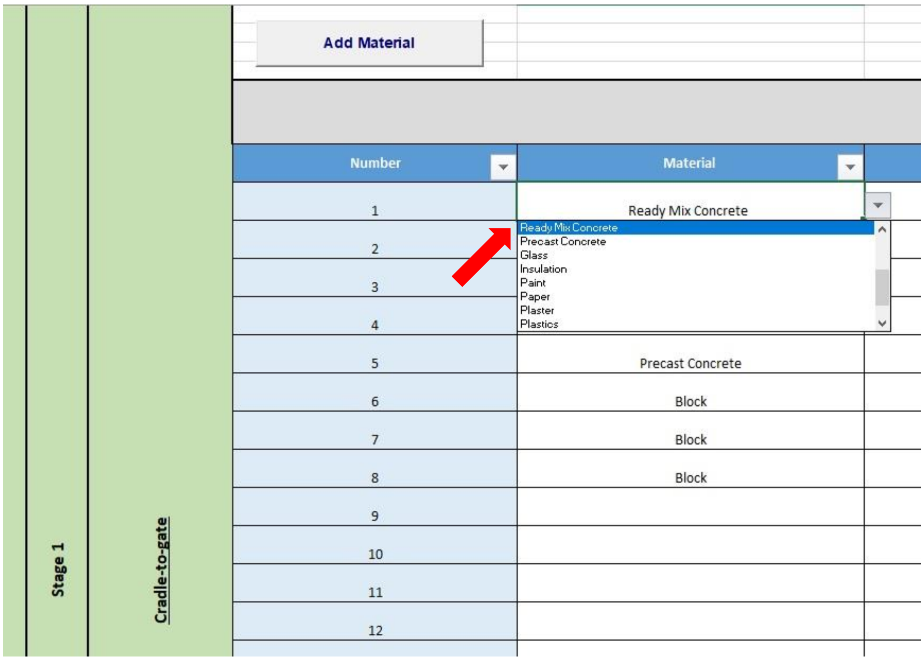

Figure 7: Material selection (Stage 1, Step 1)

B. From the drop-down list, select the type, as shown in Figure 8. The type selected here is 'RC (25–30 MPa) – 100% Portland cement (CEM I)'.

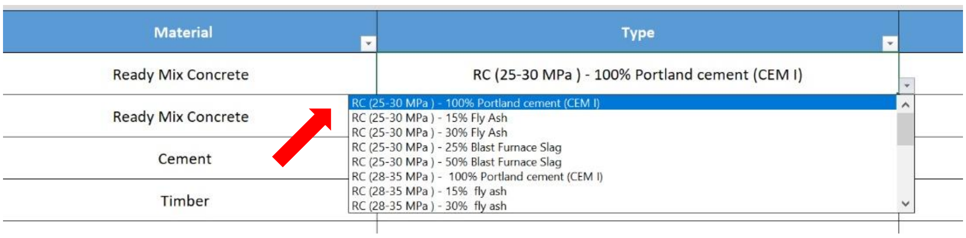

Figure 8: Type selection (Stage 1, Step 1)

[3] Where 1 MJ = 0.2778 kWh.
[4] This part should include the equations and calculations information in the user manual; however, to avoid repetition, it is advised to refer to the main body of the thesis. The actual version will contain this information.

C. Write the purpose of the selection (i.e. plain concrete, reinforced concrete, steel rebar for concrete structure). Then, enter the quantity of the material type based on the units of measurement[5], as shown in Figure 9. For this example, '76083.7 (Kg)' is entered for 'RC (25–30 MPa) – 100% Portland cement (CEM I)', and the purpose for this material is 'plain concrete for blinding (below foundations, ground beams)'.

Purpose	Unit	Quantity
Plain concrete for blinding (below foundations, ground beams)	kg	76083.7
Reinforced concrete foundations, beams, columns, slabs, stairs	kg	1870151.8

Figure 9: Quantity of material type (Stage 1, Step 1)

2.2.2.2. Step 2: Select whether 'ready-mix concrete' or 'precast concrete' is used

A. If either of the above-mentioned materials has been selected, the user may need to add details about the quantity of steel reinforcement (kg/m³) adopted therein, as shown in Figure 10. For this case study, '0 kg' of steel rebar (for every 1 m^3 of concrete) is entered[6].

Step 2: If "Ready Mix Concrete" or "Precast Concrete" is selected, add details about the quantity of steel reinforcement (kg/m³).	
Additional materials	**Quantity (kg steel rebar/m³concrete)**
Reinforcement steel - ready mix concrete	0

Figure 10: Steel reinforcement for concrete or precast concrete (Stage 1, Step 2)

B. For each 'selected material type', the results ('embodied $kgCO_2e$' and 'embodied energy (MJ)') will be automatically calculated in the same row, as shown in Figure 11. The application also provides the total for each of the selected materials in the last row of the table. For the case study, the embodied $kgCO_2e$, MJ and kWh for the selected material type 'RC (25–30 MPa) – 100% Portland cement (CEM I)' is '10651.72', '69236.17', and '19232.42', respectively.

The results for this stage will appear automatically		
Embodied $kgCO_2e$	**Embodied energy (MJ)**	**Embodied energy (kWh)**
10651.72	69236.17	19232.42
276782.47	1776644.21	493516.23

Figure 11: Summary of the results (Stage 1)

[5] As the unit for the quantity will appear automatically, it does not need to be entered manually.
[6] N.B. The user needs to skip this step if the construction does not include either 'ready-mix concrete' or 'precast concrete', in which case the screen will show 'none'.

C. To add more materials, use the option ‘add material’, as shown in Figure 12, and an extra row will appear. There is no limit on how many materials the user can add. Twenty materials are added for this case study (e.g. ready-mix concrete through to blocks).

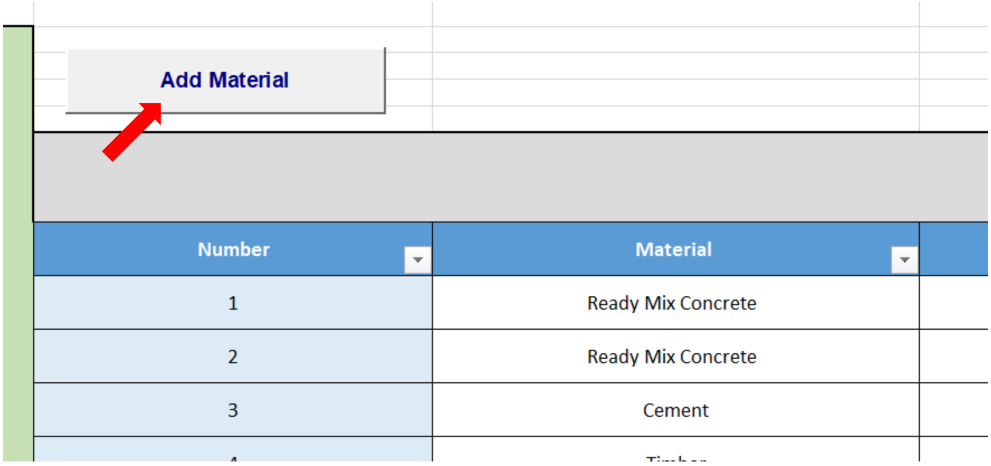

Figure 12: Addition of other materials (Stage 1)

2.2.3. Stage 2: Transport selections from the gate to the grave

In order to improve the embodied carbon kgCO_2e outcome for the construction materials, Stage 2 has been added to the framework. This stage covers the embodied kgCO_2e associated with transport activities from the gate to the grave. In stage 2, the required details of the relevant construction materials will appear automatically (within the blue cells). The quantities of all the 20 materials selected for the case study appear as shown in Figure 13. The user will need to input transportation information (see Section 2.2.3.1, noting that Stage 2 has been calculated based on Section 4.2.2 in the thesis).

These details will appear automatically based on previews adding construction material details

Number	Material	Type	Quantity (tonne)
1	Ready Mix Concrete	RC (25-30 MPa) - 100% Portland cement (CEM I)	76.0837
2	Ready Mix Concrete	RC (28-35 MPa) - 100% Portland cement (CEM I)	1870.1518
3	Cement	Mortar (1:3 cement:sand mix)	247.247
4	Timber	Timber: Plywood	32.96017
5	Precast Concrete	Precast RC (25-30 MPa) - 100% Portland cement (CEM I)	2.08224
6	Block	Autoclaved aerated block	88.02
7	Block	Concrete block: (12 MPa)	95.846
8	Block	Concrete block: (8 MPa)	787.16

Figure 13: Relevant construction materials (Stage 2)

2.2.3.1. Add transport (activity, type and distance)

A. From the drop-down list, select the category of activity[7, 8], as shown in Figure 14. The user may add up to three modes of transport. For the case study, 'HGV diesel' is selected for the category 'activity 1' for the 'ready-mix concrete'.

Activity 1	Type 1	Distance 1 - (km)
HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	14
	Rigid (>7.5 tonnes-17 tonnes)	14
	Rigid (>7.5 tonnes-17 tonnes)	139

HGV Diesel
Vans Diesel
Vans Petrol
Rail
Freight flights
Cargo ship

Figure 14: Category of activity (Stage 2, Step 1)

[7] Note that this information should cover transport from the gate to the grave, and should be completed based on the available information. The processes seen in Figure 14 and 15 will be repeated up to three times.

[8] The 'gate' refers to the gate of the factory and the 'grave' denotes the end of the life of the material (i.e. after the demolition of the building).

B. From the drop-down list, select the type of activity and add the distance (km), as shown in Figure 15. For the ‘ready-mix concrete’, ‘rigid (>7.5 tonnes–17 tonnes)’ is selected as the type of activity, and the distance is ‘14 (km)’.

Activity 1	Type 1	Distance 1 - (km)
HGV Diesel	Rigid (>7.5 tonnes-17 tonnes)	14
HGV Diesel	Rigid (>3.5 - 7.5 tonnes) Rigid (>7.5 tonnes-17 tonnes) Rigid (>17 tonnes) Articulated (>3.5 - 33t) Articulated (>33t)	14
HGV Diesel		139

Figure 15: Type of activity (Stage 2, Step 1)

C. The results for each ‘selected material’ will be automatically calculated in the rows shown in Figure 16. The application will also provide the total for all the selected materials at the end of the table in the last row. The result considers ‘freighting goods (downstream)’[9], ‘well-to-tank (WTT) (upstream)’[10] and ‘freighting goods (upstream and downstream)’, all of which are included in the value of kgCO_2e. As shown in Figure 16 , for the example ‘ready-mix concrete’ (first row), the results are:

- Freighting goods (downstream): 1063.41 embodied kgCO_2e;
- Well-to-tank (WTT) (upstream): 253.09 embodied kgCO_2e; and
- Freighting goods (upstream and downstream): 1316.51 embodied kgCO_2e.

The results for this stage will appear automatically		
Embodied kgCO_2e = Freighting goods (downstream)	Embodied kgCO_2e = Well-to-tank (WTT) (upstream)	Embodied kgCO_2e = Freighting goods (upstream and downstream)
1063.41	253.09	1316.51
26138.92	6221.10	32360.02

Figure 16: Summary of the results (Stage 2)

[9] As per the report by the Department for Business Energy & Industrial Strategy (2018) and the greenhouse gas protocol reported by Ranganathan et al. (2004), freighting goods emissions are resulted from using the fuel (e.g. diesel or petrol) during the operation of transport modes (e.g. operation of van or ship). However, it should be noted that the WTT emissions are resulted from the fuel production until it reaches the transport modes, such as those embodied from the extraction and refining of crude oil.

2.2.4. Stage 3: U-value calculations for the domestic building

The framework considers U-value calculations to reduce energy demand in residential buildings. Annual consumption (energy demand: kWh) is calculated for cooling and heating loads as well as embodied $kgCO_2e$ from cooling and heating the building (noting that Stage 3 has been calculated based on Section 4.2.3 in the thesis).

2.2.4.1. U-value for 'walls and roofs'

A. *Step 1: From the drop-down list, select the section type.*

For the case study, the section type 'roof' is selected for construction section 1 and 2, as shown in Figure 17; 'wall' is selected for construction section 3 and 4.

B. *Step 2: Add the area for this selection.*

For the case study, the total area of the roof (number 1) is 175 m^2, as shown in Figure 17.

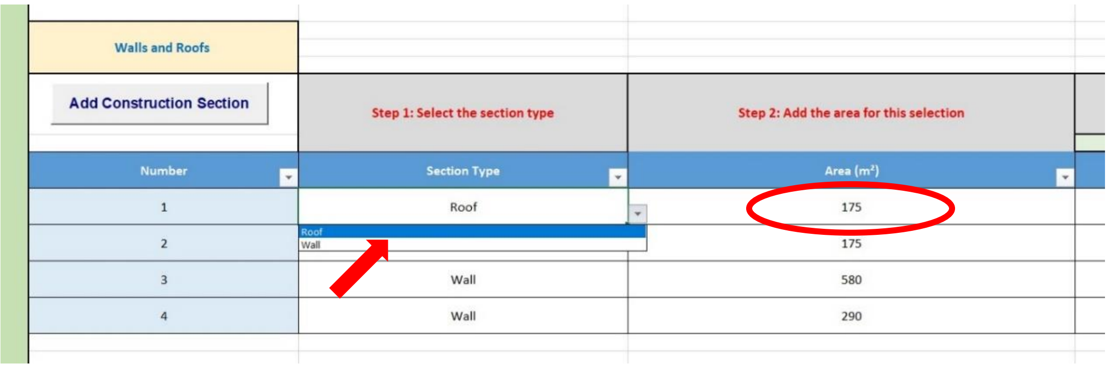

Figure 17: Section type and area (Stage 3: walls and roofs)

C. *Step 3: Add details about section layers. The user may add up to six layers (in addition to the outside and inside layers[11]).*

- From the drop-down list, select the material category, as shown in Figure 18. For 'layer 1' of the roof (material-1), the material category is selected as 'ceramic'.

Figure 18: Material category (Stage 3: walls and roofs)

[11] It is assumed that the internal thermal resistance is 0.13 and the external thermal resistance is 0.04 (both values in m²·K/W).These numbers were sourced from Everett (2018).

-As shown in Figure 19, from the drop-down list, select the material type and then enter details about the material thickness. For ‘layer 1’ of the roof, the material type is ‘glazed’ and the thickness is ‘0.02 (m)’.

Material - 1	Type - 1	Material Thickness (m) - 1
Ceramic	glazed	0.02
Soil	earth, gravel-based	0.03
Stone	granite	0.02

Figure 19: Material type and thickness (Stage 3: wall and roof)

- Regarding the selection of the material and its type, the specifications ‘condition/test (where known)’, ‘source’, ‘density (kg/m³)’, ‘specific heat capacity (J/kg·K)’ and ‘thermal conductivity (W/m K)’ will appear, as shown in Figure 20 (this will help the user to make decisions about the choices[12]). For ‘layer 1’ of the roof, the properties are as follows: density ‘2500 (kg/m³)’; specific heat capacity ‘840 (J/kg·K)’; thermal conductivity ‘1.4 (W/m K)’; source ‘Institut Belge de Normalisation, Belgium’; and no condition/test where known.

Condition/test (where known) - 1	Source - 1	Density (kg / m³) - 1	Specific heat capacity (J/kg·K) - 1	Thermal conductivity (W/m K) - 1
0	Institut Belge de Normalisation, Belgium	2500	840	1.4

Figure 20: Material specifications (Stage 3: walls and roofs)

- The results for each construction section will be automatically calculated, as shown in Figure 21. For the case study, after all the layers are added, the roof resistance (R-value) is ‘1.06 (m² K /W)’, its conductance (U-Value = 1/R) is ‘0.95 (W/ m² K)’ and its contribution to the gain or loss coefficient is ‘165.57 (W K^{-1})’.

Resistance (m² K/W)	U-Value (W/m²K)	Contribution to heat gain or loss coefficient (/W K^{-1})
1.06	0.95	165.57

Figure 21: Summary of the results (Stage 3: walls and roofs)

[12] It is recommended that the user visit the page ‘Data 2’ in the application to check all details about the materials. They may find the same ‘material type’ with different specifications (e.g. ‘general 1’ and ‘general 2’ in ‘asphalt’). Also on the page ‘Data 2’, the user will find the table for the codes and source references. The basic data were obtained from CIBSE (2018).

- Note: If the user prefers to add more construction sections, they should use the option 'add construction section', as shown in Figure 22, and an extra row will appear. There is no limit to how many construction sections can be added. The case study includes two types of walls ('external wall') and two types of roofs.

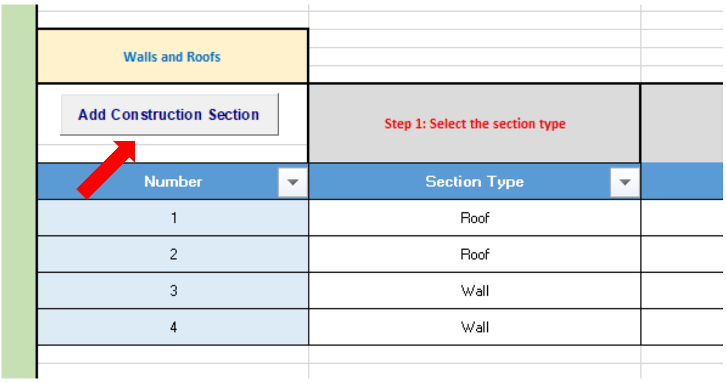

Figure 22: Add construction section (Stage 3: walls and roofs)

2.2.4.2. U-value for 'glazing'

A. Step 1: Select the glazing properties.

- From the drop-down list, select the type of frames, as shown in Figure 23. For the case study, the type of frames is 'metal frames 8mm thermal break'.

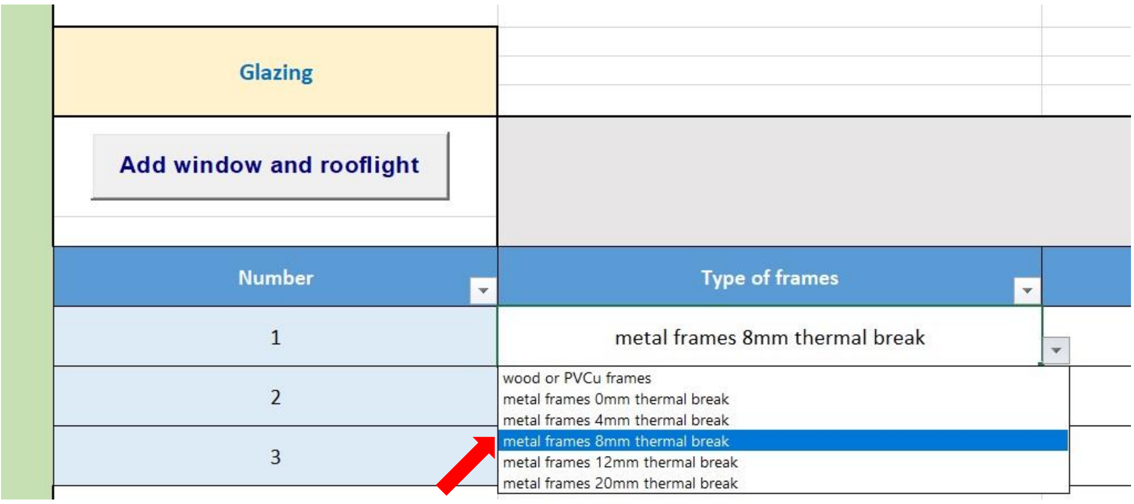

Figure 23: Type of frames (Stage 3: glazing)

- From the drop-down list, select the type of glazing, as shown in Figure 24. In the case study, ‘double glazing (low-E, εn = 0.1, air filled)’ is selected as the type of glazing.

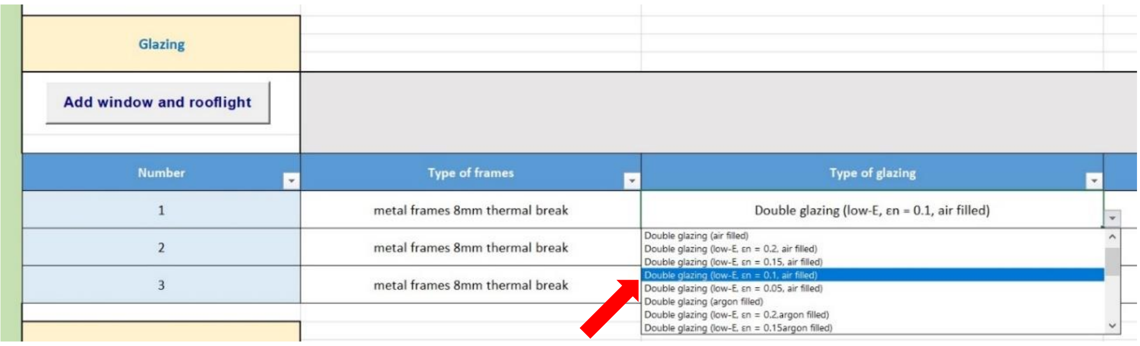

Figure 24: Type of glazing (Stage 3: glazing)

- From the drop-down list, select the gap between the panes[13], as shown in Figure 25. For the case study, the gap between the panes is ‘12 mm’.

Figure 25: Gap between the panes (Stage 3: glazing)

- From the drop-down list, select the conditions (‘window’ or ‘rooflight’), as shown in Figure 26. For the case study, the selection is ‘window’.

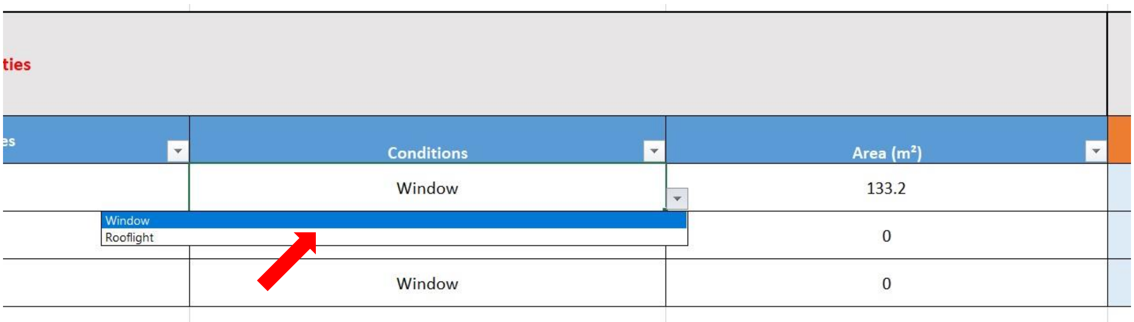

Figure 26: Conditions for window or rooflight (Stage 3: glazing)

[13] Select ‘not applicable’ when the selection is single-glazed (do not select ‘not applicable’ when the selection is double- or triple-glazed).

- Enter the area (m²), as shown in Figure 27. When entering the area, the user should count the total area of this selection. For the case study, the area for the selection is ‘133.2 (m^2)’.

Conditions	Area (m²)
Window	133.2

Figure 27: Area for window or rooflight (Stage 3: glazing)

- If the user prefers to add more windows or rooflight types, they should use the option ‘add window and rooflight’, as shown in Figure 28, and an extra row will appear. There is no limit to how many times this option can be used. The case study has only one type of window.

Glazing

Add window and rooflight

Number	Type of frames
1	metal frames 8mm thermal break
2	metal frames 8mm thermal break
3	metal frames 8mm thermal break

Figure 28: Add window or rooflight (Stage 3: glazing)

B. ***For each selected ‘window’ or ‘rooflight’ types, the results will be automatically calculated, as shown in Figure 29.***

- For the first type, the U-value is ‘2.5 (W/m^2.K)’ and the contribution to the gain or loss coefficient is ‘333 (W K^{-1})’.

Results for this stage will appear automatically

U-values (W/m2·K)	Contribution to heat gain or loss coefficient (W K^{-1})
2.5	333

Figure 29: Summary of the results (Stage 3: glazing)

2.2.4.3. U-value for 'ground floor'

A. Step 1: Enter the ground floor area and perimeter, as shown in Figure 30.

- For the case study, the ground floor area is '381 (m^2)' and the perimeter is '95 (m)'.

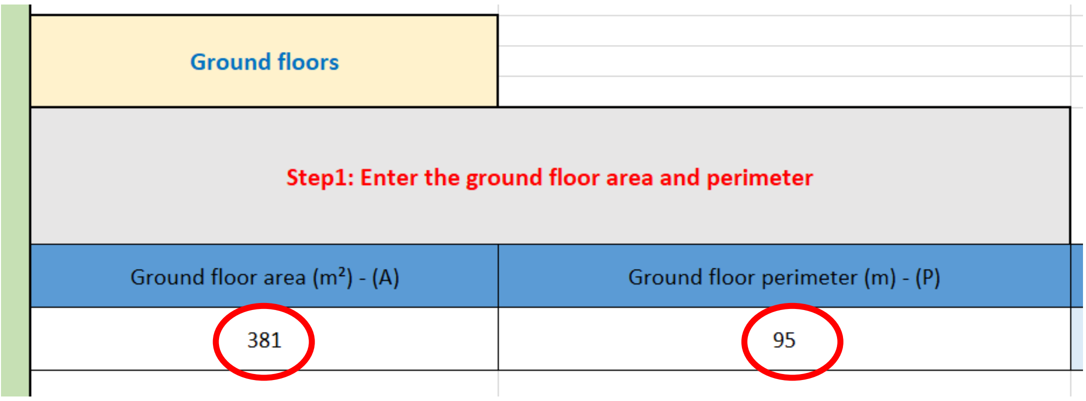

Figure 30: Ground floor area and perimeter (Stage 3: ground floor)

B. Step 2: Select the soil type from the drop-down list, as shown in Figure 31.

- For the case study, the soil type is 'sand or gravel'.

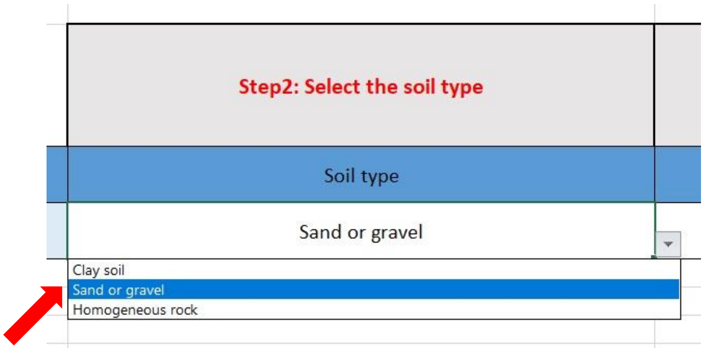

Figure 31: Soil type (Stage 3: ground floor)

C. Step 3: Select the insulation type from the drop-down list. Then, enter the thickness of the insulation material, as shown in Figure 32.

- For the case study, 'polyurethane, expanded' insulation of '0.01 (m)' thickness is selected.

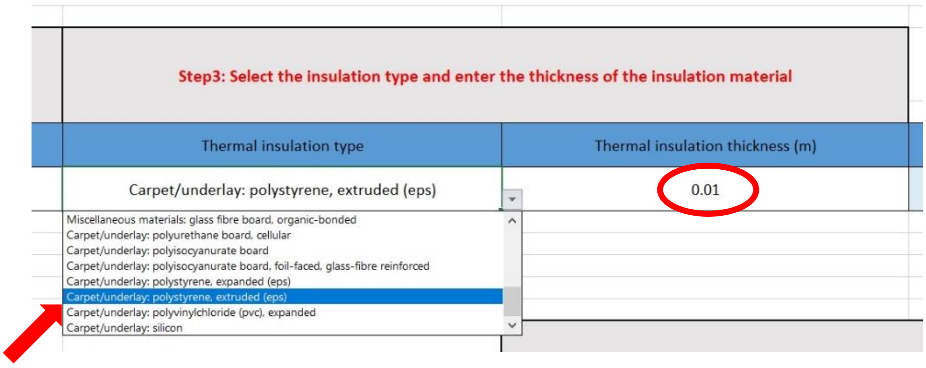

Figure 32: Insulation type and thickness

(Final version)

The results[14] for the 'ground floor' selection will be automatically calculated, as shown in Figure 33. For the first type, the U-value is '0.41 (W/m^2.K)' and the contribution to the gain or loss coefficient is '156.21 (W K^{-1})'.

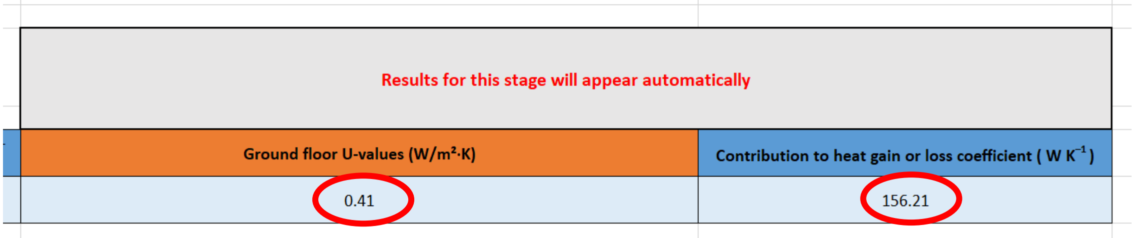

Figure 33: Summary of the results (Stage 3: ground floor)

2.2.4.4. Annual consumption (energy demand) for cooling or heating load

This section will provide an overview of annual consumption (energy demand) which will reflect the following previous selections: 'wall and roofs', 'glazing' and 'ground floor'[15]. In addition, it will reflect 'house ventilation' and 'cooling and heating degree' which will be presented for selection at this stage.

A. Step 1: Select a city from the drop-down list, as shown in Figure 34.

- For the case study, Dammam city is selected as the location.

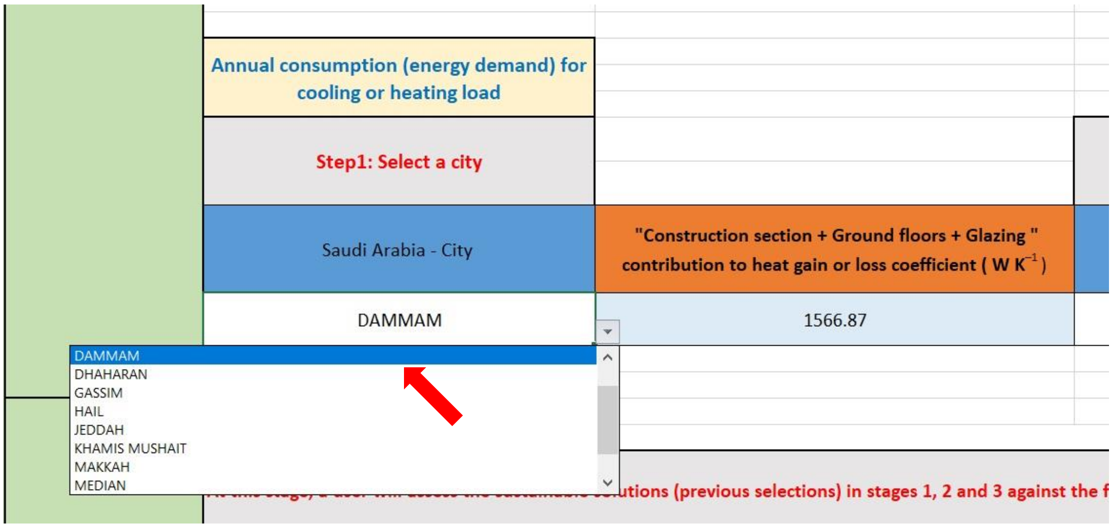

Figure 34: Location (city) (for calculation of annual energy demand)

[14] The result of the U-value will appear based on criteria tables sourced from CIBSE (2018).

[15] Figure 34 shows the total contribution to the heat gain or loss coefficient of a house (1566.87 W K^{-1}) which is calculated from the sum 'construction section + ground floors + glazing' in the previous sections.

B. Step 2: Enter the volume of the house from the drop-down list, as shown in Figure 35.

Figure 36 provides the contribution of ventilation to the heat gain or loss coefficient (W K^{-1}). For the case study, the house volume is '3735 (m^3)' and the contribution of ventilation to the heat gain or loss coefficient is '431.39 (W K^{-1})'.

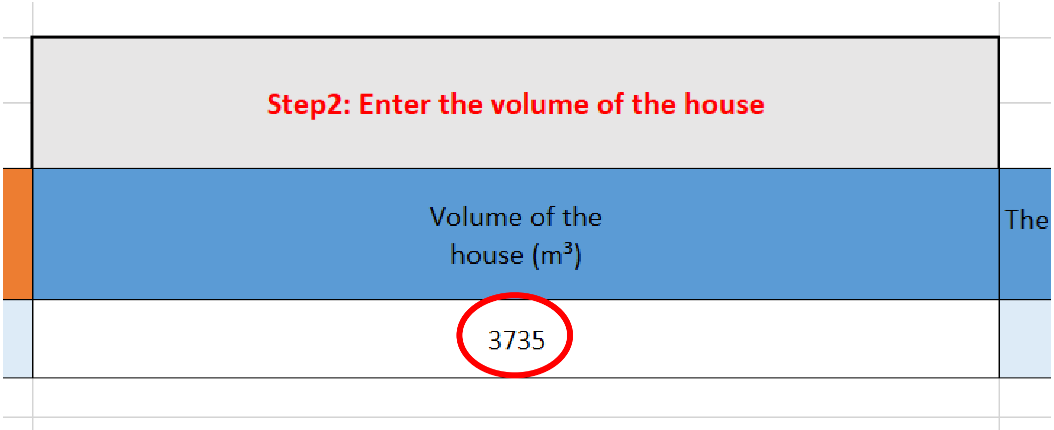

Figure 35: Volume of the house (for calculation of annual energy demand)

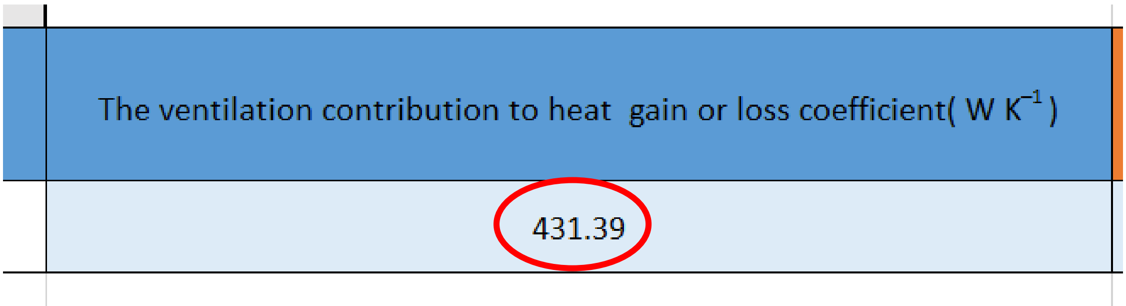

Figure 36: Contribution of ventilation to heat gain or loss coefficient

C. ***The results of the annual energy demand of the house will be automatically calculated, as shown in Figure 37. The results include the annual consumption 'energy demand (kWh)' for the cooling and heating loads and the annual 'embodied (kgCO_2e)' which is derived from energy consumption.***

For the case study shown in Figure 37, the following are the results of annual energy demand for the house:

- Annual consumption – energy demand for cooling load (kWh): 166080
- Annual consumption – energy demand for heating load (kWh): 10215
- Annual consumption – energy demand (kWh) for cooling and heating load: 176295
- Annual consumption – embodied (kgCO_2e) for cooling load: 120574
- Annual consumption – embodied (kgCO_2e) for heating load: 7416
- Annual consumption – embodied (kgCO_2e) for cooling and heating load: 127990

(Final version)

Results for this stage will appear automatically					
Annual consumption – energy demand for cooling load (kWh)	Annual consumption – energy demand for heating load (kWh)	**Annual consumption – energy demand (kWh) for cooling and heating load**	Annual consumption – embodied ($kgCO_2e$) for cooling load	Annual consumption – embodied ($kgCO_2e$) for heating load	**Annual consumption – embodied ($kgCO_2e$) for cooling and heating load**
166080	10215	176295	120574	7416	127990

Figure 37: Summary of the results (for calculation of annual energy demand)

2.2.5. Stage 4: Assessing the resilience of possible sustainable solutions in the future

Today, it should not be unusual for building designs to incorporate considerations of sustainability and resilience (in addition to adaptability and liveability; Rogers, 2018). As reported by Rogers (2018), civil engineers must be provided with support to improve how their interventions (in this case materials) are conceived, prepared and implemented so that they align with these concepts and are able to adapt to changing circumstances in the future.

With the environmental sustainability of material selection having been assessed in Filter 1, the assessment of resilience is undertaken in Filter 2 (see Figure 1 in Section 1.1). This secondary filtering process is based upon an 'urban futures assessment' of the future performance of materials selected in Stages 1, 2 and 3 (i.e. the outcome of the Filter 1 process) in the context of three distinct future scenario archetypes: (1) market forces[16]; (2) policy reform[17]; and (3) new sustainability paradigm[18] (see Raskin et al., 2002; Hunt et al., 2012).

In order to do this, a number of necessary conditions (that is, conditions necessary to allow the selected materials to deliver their function in the long term) should be derived (Lombardi et al., 2012). These are shown in Table 4.

Table 4: Necessary conditions for materials used in domestic buildings

No	Necessary conditions
1	Availability of proposed materials
2	Bouncebackability of the building
3	Absence of other environmental considerations
4	Minimum building code requirements
5	Environmental footprint of transport
6	Public acceptance of sustainable solutions

Table 5: An example resilience matrix for assessing materials (modified from Lombardi et al., 2012)

Necessary conditions	New sustainability paradigm	Policy reform	Market forces
(A)	Green	Green	Green
(B)	Green	Green	Amber
(C)	Red	Amber	Red

[16] A conventional scenario, sometimes referred to as business-as-usual, where no major changes to current patterns of behaviour are expected. In terms of material selection, this would likely mean that sustainability does not feature high on the agenda, and the aesthetics (i.e. form) and function of a material waste is considered far more readily than sustainability credentials.
[17] Based on strict policy to achieve sustainability goals. In terms of material choice, sustainability is likely to feature much higher on the agenda, enforced by strict policies for improving material selection.
[18] It is led by the widely accepted sustainable citizen values and behaviour. For material selection it is likely that citizens readily embrace sustainable material choice and the governance systems support such implementation.

The matrix in Table 5 is used to evaluate the necessary conditions for the sustainable solution (selected materials) regarding their performance in three future scenarios. This evaluation is to decide whether these solutions should be implemented, adapted or replaced by other solutions which will go through the evaluation process again (Lombardi et al., 2012). In each of these future scenarios, there are three grade levels that assess whether the necessary conditions are respected. They are as follows:

- Green: a condition highly likely to continue in the future.
- Amber: a condition at risk in the future.
- Red: a condition highly unlikely to continue in the future.

If green grade has been allocated in all three scenarios, such as condition (A), there is the possibility that this solution (the proposed material choice) can be utilised with confidence. However, if amber or red grades are allocated to one of the three future scenarios, such as conditions (B) and (C), for example, it simply means that the proposed solution is not fully resilient in the case of condition (B) and not resilient at all in the case of condition (C). Both require more research for the possibility of the adaptation or conceptualization of other alternative (more resilient) solution(s) (note that accepting the highlighted risks might be possible in condition (B) but not in condition (C)). (The user is expected to use the fill colour icon to grade the scenario; see Figure 38.)

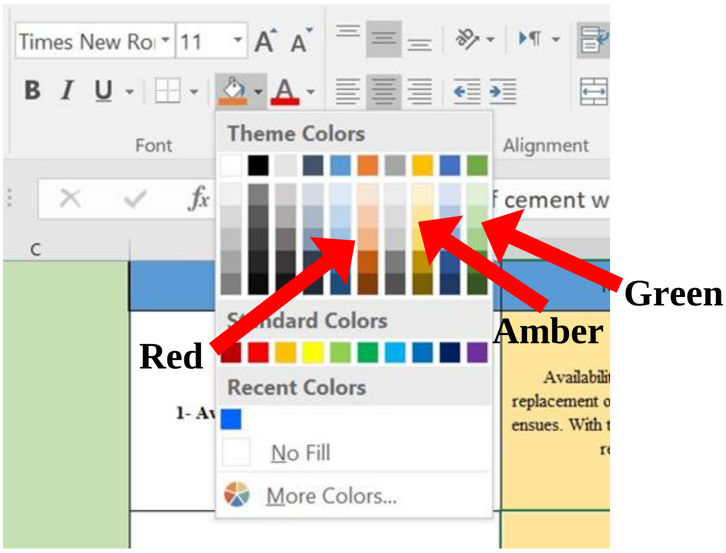

Figure 38: How to grade the scenarios using colours

In brief, using a resilience filter and matrix in this way is like brainstorming the future-proof-ability of the proposed solution. For example, when a government body introduces a new policy that enforces the use of a particular construction material, this policy may not be implemented correctly in practice because the market may be unable to supply enough of this material to meet demand.

2.2.6. Part 2: Results (output)

A. A summary of the results will appear as graphs and tables on the main page.

- For the case study, the total embodied $kgCO_2e$ for 'ready-mix concrete' was highest among all the materials. Figure 39 reports details for both 'cradle-to-gate' in blue and transportation ('gate-to-grave') in orange. The framework can provide additional details; there are seven figures that present the results.

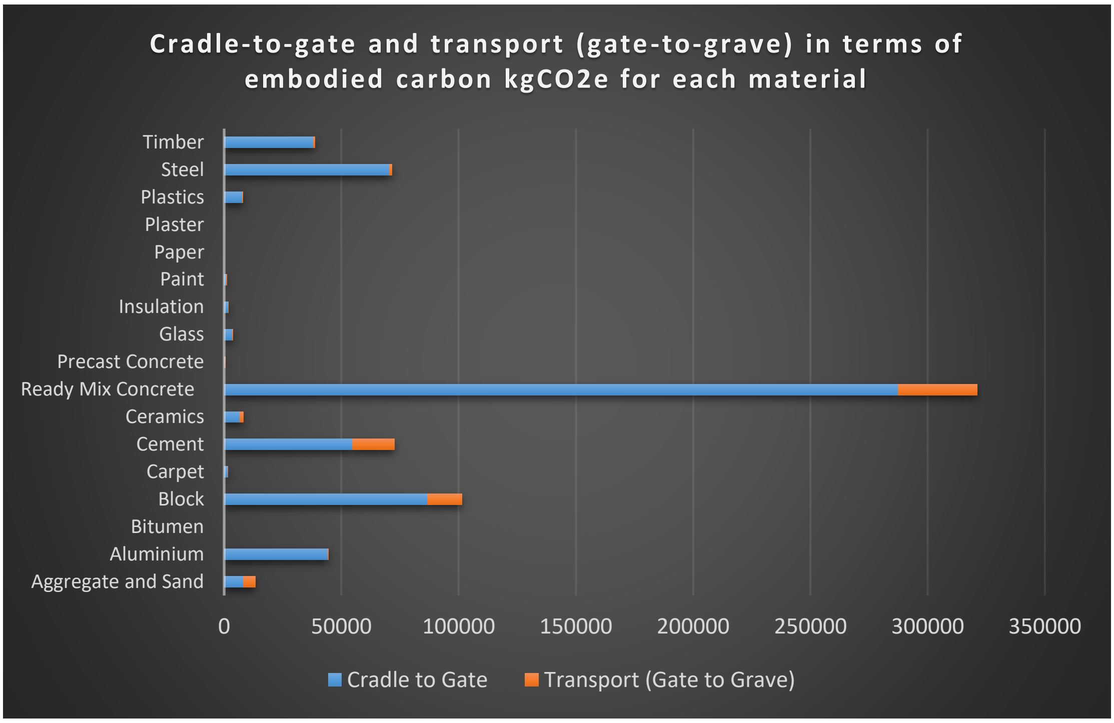

Figure 39: Example of final results (figures)

- For the case study, the table in Figure 40 presents the total embodied $kgCO_2e$ for all the materials: approximately 612403.68 $kgCO_2e$ for cradle-to-gate and 75117. $kgCO_2e$ for transportation (gate-to-grave). Refer to the framework for additional details of the results.

Material	Embodied $kgCO_2e$	Embodied $kgCO_2e$
	Cradle to Gate	Transport (Gate to Grave)
Aggregate and Sand	8154.85	5139.82
Aluminium	44270.28	94.41
Bitumen	0.00	0.00
Block	86715.65	14784.62
Carpet	1483.68	26.21
Cement	54641.59	17978.17
Ceramics	6629.22	1594.39
Ready Mix Concrete	287434.18	33676.53
Precast Concrete	351.90	31.70
Glass	3577.50	77.57
Insulation	1748.70	12.02
Paint	983.00	33.93
Paper	0.00	0.00
Plaster	0.00	0.00
Plastics	7810.04	41.84
Steel	70516.51	1109.76
Timber	[illegible]	[illegible]
Total	612403.68	75117.91

Figure 40: Example of final results (tables)

B. A summary of the results will appear as graphs and tables on a separate page called 'key results'.

To shape up the sustainable environmental results, and to have them be in line, a new section called 'key results' is created on a separate page (see Figure 41). The main function of this page is to summarise the results in a simple and brief way.

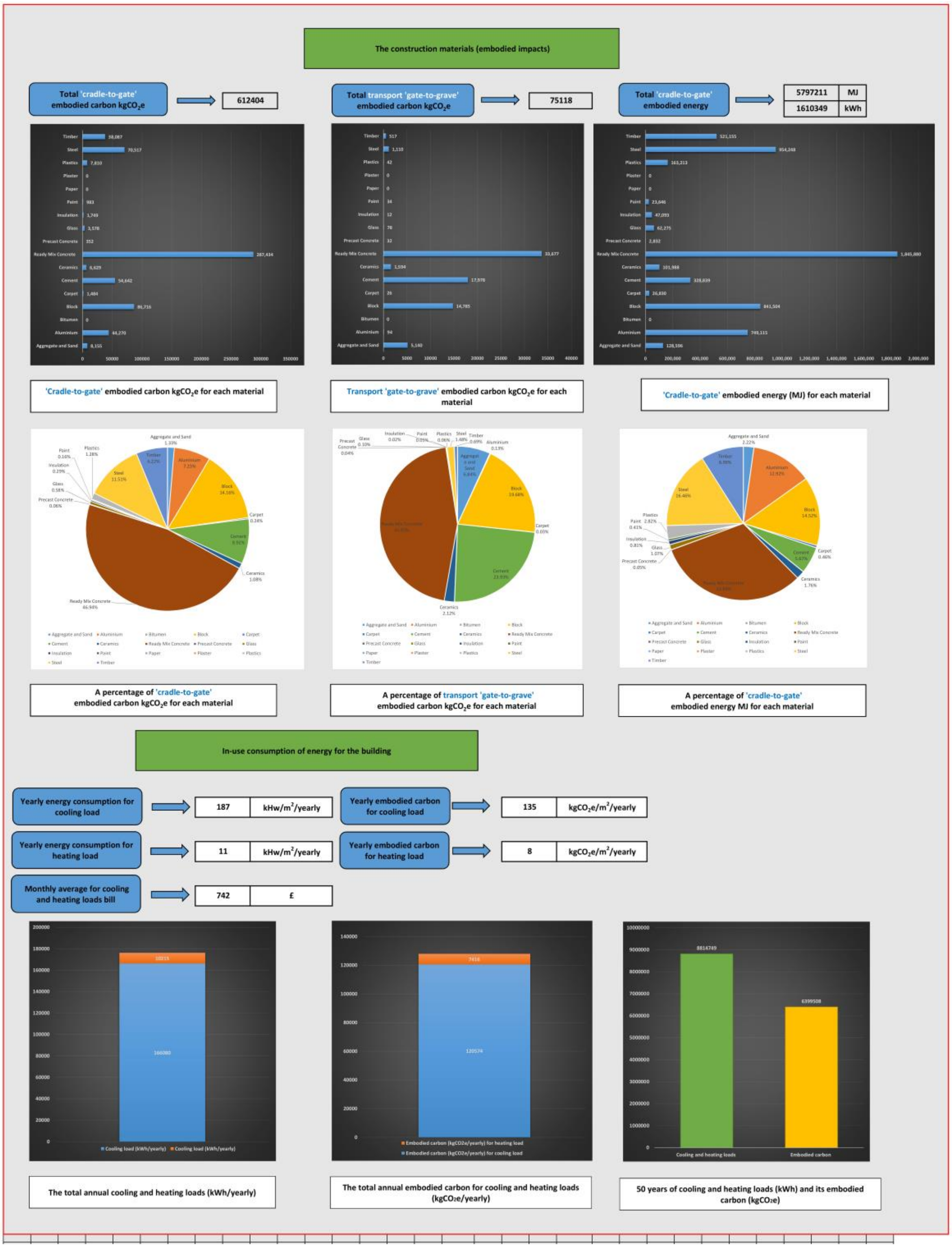

Figure 41: The new page for environmental sustainability results

C. *Hints of how to use the RESAF to improve the environmental effects and the resilience assessment.*

Applying the RESAF to a case study is a process that involves discovering many alternatives until the design needs (or in other words, user requirements) are reached. A user target is to reduce energy and carbon from construction materials (embodied) and from the cooling and energy demands during the in-use stage.

There are a number of ways that can be used to reduce the environmental effects:

1. Replace some construction materials with materials with low embodied carbon and energy; for example, partially substitute the cement with replacement materials when using ready-mix concrete using pulverised fly ash or ground granulated blast furnace slag. The user is advised to consult the data for materials' embodied carbon and energy coefficients (Hammond and Jones, 2011a), which can be found within the Microsoft Excel file page **'Data'.**
2. In the in-use building cooling and energy demands, the main role is to reduce the U-values for the building elements. For example, the user can change the type of windows or change properties of the walls and roofs (such as increase the thickness of insulation or type of insulation). Again, it is recommended that the user consult the data on the materials' properties (in particular, thermal conductivity) from CIBSE (2018) which can be found within the Microsoft Excel file page **'Data 2'**; they should also consult the indicative U-values ($W/m^2{\cdot}K$) for windows or ground floor, which can found be found within the Microsoft Excel file page **'Data 3'**.
3. Changes in point 1 and 2 will reflect each other, so the user should take this into account. For example, increasing the insulation thickness will increase the quantity of the insulation (the user should change this accordingly).
4. The user can change the information in the pages called '**Data'**, **'Data 2'** and **'Data 3'**. For example, in Figure 42 the user can change an indicative U-value for windows on the page **'Data 3'** simply by editing the numbers shown in Figure 42, and then pressing save (this applies for all data – as all data are editable and can be changed by the user if necessary).

An example proposing changes is as follows:

A. Use ready-mix concrete, replacing the cement with 50% blast furnace slag (Stage 1).
B. Replace autoclaved aerated blocks with concrete blocks (8 MPa) (Stage 1). Therefore the quantity of concrete blocks (8 MPa) will increase from 787,160 kg to 941,195 kg (in Stage 1).
C. Walls and roofs: increase the thickness of the extruded polystyrene from 20 mm to 30 mm (in Stage 3: walls and roofs U-values). Note that the user will need also to increase the quantity of extruded polystyrene from 531.52 kg to 734.04 kg (in Stage 1).

D. Replace the double glazing with triple glazing and keep the aluminium frame (Stage 3: U-value for 'glazing'). Note that the user will also need to increase the quantity of glass from 2,650 kg to 3,975 kg (in Stage 1).

In Table 6 these changes will reduce the energy and embodied carbon by 11.63 and 21.76 %, respectively, while the yearly energy consumption and embodied carbon during the in-use stage is reduced by 17%.

Table 6: Reporting savings by using the RESAF

	Base case	After a modification (A to C) is applied to the base case
Embodied energy from materials	5,797,214 MJ or 1,610,349 kWh	5,123,081 MJ or 1,423,090 kWh (11.63 savings)
Embodied carbon from materials	612,406 $kgCO_2e$	479,175 $kgCO_2e$ (21.76% savings)
Yearly energy consumption (in-use stage)	176,295 kWh (198 kWh/m^2)	145,792 kWh (164 kWh/m^2) (17% savings)
Yearly embodied carbon (in-use stage)	127,990 $kgCO_2e$ (144 $kgCO_2e/m^2$)	105,845 $kgCO_2e$ (119 $kgCO_2e/m^2$) (17% savings)

		(CIBSE , 2018) Indicative U-values ($W/m^2 \cdot K$) for windows					
		Gap between panes				Adjustments to U-values	
Frames	Types	6mm	12mm	16mm	not applicable	Window	Rooflight
wood or PVCu frames	Windows and doors , single-glazed	#N/A	#N/A	#N/A	4.8	0	0.5
	Windows with secondary glazing	#N/A	#N/A	#N/A	2.4	0	0.5
	Double glazing (air filled)	3.1	2.8	2.7	#N/A	0	0.3
	Double glazing (low-E, εn = 0.2, air filled)	2.7	2.2	2.1	#N/A	0	0.3
	Double glazing (low-E, εn = 0.15, air filled)	2.7	2.2	2	#N/A	0	0.3
	Double glazing (low-E, εn = 0.1, air filled)	2.6	2.1	1.9	#N/A	0	0.3
	Double glazing (low-E, εn = 0.05, air filled)	2.6	2	1.8	#N/A	0	0.3
	Double glazing (argon filled)	2.9	2.7	2.6	#N/A	0	0.3
	Double glazing (low-E, εn = 0.2,argon filled)	2.5	2.1	2	#N/A	0	0.3
	Double glazing (low-E, εn = 0.15argon filled)	2.4	2	1.9	#N/A	0	0.3
	Double glazing (low-E, εn = 0.1, argon filled)	2.3	1.9	1.8	#N/A	0	0.3
	Double glazing (low-E, εn = 0.05, argon filled)	2.3	1.8	1.7	#N/A	0	0.3
	Triple glazing (air filled)	2.4	2.1	2	#N/A	0	0.2
	Triple glazing (low-E, εn = 0.2, air filled)	2.1	1.7	1.6	#N/A	0	0.2
	Triple glazing (low-E, εn = 0.15, air filled)	2.1	1.7	1.6	#N/A	0	0.2
	Triple glazing (low-E, εn = 0.1, air filled)	2	1.6	1.5	#N/A	0	0.2
	Triple glazing (low-E, εn = 0.05, air filled)	1.9	1.5	1.4	#N/A	0	0.2
	Triple glazing (argon-filled)	2.2	2	1.9	#N/A	0	0.2
	Triple glazing (low-E, εn = 0.2, argon filled)	1.9	1.6	1.5	#N/A	0	0.2
	Triple glazing (low-E, εn = 0.15, argon filled)	1.8	1.5	1.4	#N/A	0	0.2
	Triple glazing (low-E, εn = 0.1, argon filled)	1.8	1.5	1.4	#N/A	0	0.2
	Triple glazing (low-E, εn = 0.05, argon filled)	1.7	1.4	1.3	#N/A	0	0.2

Figure 42: Example of editing the data information in the framework

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