AMERICAN UNIVERSITY OF BEIRUT

A DECISION SUPPORT SYSTEM TOOL FOR SELECTING AND IDENTIFYING OFF-SITE CONSTRUCTION SYSTEMS AND COMPONENTS

by
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AN ABSTRACT OF THE THESIS OF

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Title: A Decision Support System Tool for Selecting and Identifying Off-Site Construction Systems and Components

Many studies have shown the positive impact of applying lean principles in off-site construction. Although efforts were channeled towards comparing off-site versus on-site construction systems, none has performed a comparison among off-site non-volumetric systems (e.g. panelized and natural materials), volumetric systems, and hybrid systems. Additionally, none have performed a granular comparison among the off-site system components. They have only focused on different types of off-site construction without sufficiently considering and comparing their respective attributes. In fact, off-site systems and components present different advantages and disadvantages implying a need to evaluate their value maximization in terms of cost, time, quality, etc. Therefore, this research study presents a decision making evaluation tool targeted at: (1) extracting and elaborately analyzing the attributes associated with the different off-site systems and components, (2) identifying the optimal off-site systems for a given project by resorting to the Analytical Hierarchy Process technique (AHP), and (3) identifying the optimal components through a Choosing by Advantage technique (CBA). The outcomes of this study will yield standardized policies for properly choosing optimal off-site systems and components based on lean principles.

CONTENTS

ILLUSTRATIONS

TABLES

ABBREVIATIONS

OSC Off-Site Construction

DSS Decision Support System

AHP Analytic Hierarchy Process

CBA Chossing by Advantages

CHAPTER 1

INTRODUCTION

1.1 Introduction

On-site construction method is defined when the construction is built on site after the design is done and the contractor is hired. This method is usually called as “site-built”, “stick-built”, “on-site”, “conventional”, or “traditional” construction. Traditional construction has been the most popular method since the end of the 19th century. For instance, this method accounted for 75% of the total projects constructed in the U.S. in 1998 (Kamali et al., 2016). More recently, engineers have proposed a new approach that combines manufacturing with the construction field. As a result, off-site construction appeared as an alternative modern method to traditional one to achieve the benefits of the automotive manufacturing in construction (Vernikos et al., 2013). Nowadays, this method represents a significant part of the total building industry. In an off-site construction we have two strategies, which are product and process approaches. The first approach focuses on decreasing the onsite activities by changing the construction of buildings into products that can be manufactured in a factory environment. The second aims to apply a manufacturing mind to the construction processes (Firoozi et al., 2017).

Off-site construction is one of the construction strategies that use the principles of industrialization in the construction projects. After World War II, this technology became one of the major construction methods in many developed countries, because it was tested and applied to provide soldier accommodation during the war (Arditi et al., 2000; Musa et al., 2015). However, it didn’t get the full attention of both academia and industry up until the last few years (Kamali et al., 2016). Engineers have increasingly turned to use the off-site method as an effective alternative method to the traditional one and this method has spread among developed regions such as North America, Japan, and in parts of Europe due to its ability to increase productivity on site. Shorter construction times and tighter control on quality have also been strong motivators in the push towards increasing use of off-site elements in these regions. However, the use of this alternative method in developing regions has not been widely adopted.

The differences between the on-site and off-site method are two points: firstly, in the traditional method, the materials are brought to the construction site. While in the modern one, the materials are brought to the off-site factory where the components are produced in a factory (they are moved within the factory to get closer to the resources). Secondly, the team management in the on-site project is easier than the off-site one and that is due to the need to juggle between several modules at the same time (Nasereddin et al., 2006).

Studies about off-site construction in Lebanon and Syria are limited in the literature. Therefore, the purpose of this study is to carry out the initial steps to better assess the off-site method in the Lebanese and Syrian construction sector. In order to achieve this assessment, there is a need to improve the process of using off-site construction by studying the effects of utilizing this method, and capturing the different attributes of off-site systems and its components to highlight the difference among off-site forms. There is also a need to study the multi-attribute decision making process by using the Analytic Hierarchy Process (AHP) and Choosing by Advantages (CBA) to optimize the different client's objectives for each given project. The results of this study is to propose policies that would enhance the decision making process that is needed to opt the most suitable off-site systems and components while maximizing benefits.

1.2 Study process

A study process is adopted to conduct this research work in properly planned phases from the start of study till its completion. This process aids in defining the study gaps and problems in the research area, conceiving a series of study questions and accomplishing the aimed study goals throughout a well-built methodology. The first stage of the study process includes a thorough literature review on past studies tackling the off-site technology in construction. The research concentrates on exploring the concept of off-site construction and the methods of employing it in different construction projects. After that, the study proceeds with identifying the advantages and disadvantages of using different off-site systems. This leads to pinpointing gaps in previous studies and problems associated with off-site construction. Hence, the motive of this research is formed and the goals of the study are expanded. Thereafter, particular study questions are stated and utilized as a guide for establishing the study methodology. A well-built methodology is adopted to help in defining different features of the several existing off-site systems and components. A decision support system is provided and discussed to maximize the value of utilizing the off-site method. Conclusions and recommendations of this study are finally summarized.

1.3 Organization of the thesis

The organization of this study is summarized in Figure 1. Chapter 2 provides discussion on previous studies tackling various off-site methods. This chapter briefs: the division of off-site construction into several classifications, a description of the features for off-site systems, the advantages and disadvantages of using off-site method, the various decision support systems applied in construction and finally the major decision support systems to select the optimal off-site strategy. Chapter 3 highlights the study gaps and problems to identify the study objectives and questions. Chapter 4 illustrates the established study methods and methodology. A research for all available off-site systems and components in Lebanon and Syria is demonstrated in Chapter 5, where the attributes of these components are analyzed. A development of the decision support system through analytic hierarchy process (AHP) and choosing by advantages (CBA) is explained in Chapter 6. Chapter 7 includes analysis and discussion of the results. Conclusions of the study work, recommendations for future studies and limitations of this study are presented in Chapter 8.

Chapter 1
Introduction

- Introduction
- Research process
- Organization of the thesis

Chapter 2
Background Research

- The classification and categories of off-site construction
- The advantages and disadvantages of utilizing off-site construction
- Decision support system

Chapter 3
Research Motivation and Objectives

- Problem statement and motivation
- Research objectives
- Research questions

Chapter 4
Research Methodology and Methods

- Research methodology and methods

Chapter 5
Forms of Off-Site Construction

- Off-site systems and components

Chapter 6
Development of the Decision Support System

- Analytical heirarchy process model
- Choosing by advatages model

Chapter 7
Analysis and Discussion of Results

- Analysis and discussion of the AHP survey results
- Analysis and discussion of the CBA results

Chapter 8
Conclusions and Recommendations

- Summary and conclusions
- Recommendations for research and practitioners
- Limitations of the study

Figure 1 – Organization of the thesis

CHAPTER 2

BACKGROUND RESEARCH

A major factor contributing to the increase in construction rate is the increase in population size. This increase in the rate of construction triggered several academicians to search for new methods of construction, which led to the revival of off-site construction (Mesaros et al., 2015). Previous studies discussed aspects related to the off-site construction methods to assist in understanding the details about this modern method. These aspects include the division of the off-site construction into several classifications, a description of the features for every off-site system, the obtained advantages and disadvantages when utilizing off-site method, the different decision support systems that are applied in construction, and finally the major decision support systems to select the optimal off-site strategy.

2.1 The classification and categories of off-site construction

As perceived by Koskela, (1992) construction is a production process requiring flow of resources and information to create value for customers. Therefore, several concepts and terms were adopted from the manufacturing process for application in the construction process. These new construction methods include the off-site construction (Slaughter, 1998).

As discussed in Spisakova et al., (2017), the off-site construction was divided into several categories. For example, Warszawski (1999) divided the off-site systems according to the main framing components, into three categories namely the linear system (also known as the skeleton system), two dimensional system or panel system, and box system or three-dimensional system. The off-site systems were then divided into five categories as described by The Housing Corporation (2000). These categories included innovative traditional methods of construction, sub-assemblies systems and components, panelized systems, volumetric systems, and hybrid systems. Later, four classifications of off-site systems which include the block work system, timber or steel frame system, precast concrete framing panel and box system were determined (CIDB, 2003).

Finally, a detailed classification had been introduced by the current practices and future potential in modern methods of construction's report. This classification included the following categories: prefabricated panel, prefabricated light weighted ceiling, prefabricated cladding system, wood and light steel frame, composite insulated sandwich panel, insulated concrete formwork, kitchen and bathroom pod, and volumetric components (Hartley et al., 2007).

In short, off-site systems can be classified into different levels based on the product's manufacturing process (Shen et al., 2014). The first level, sub-assembly and component manufacturing involves small scale elements assembled in the factory environment (e.g. windows). Second, the non-volumetric manufacturing includes pre-assembled units that do not enclose a usable space, for example the timber panels (like the timber panels). On the contrary, the volumetric manufacturing consists of the pre-assembled units enclosing usable space. These units are being manufactured inside the factory without forming the part of the building's structure (like the bathrooms and kitchens). Finally, the complete manufacturing, also known as the modular construction, means the pre-assembled volumetric units form as a part of the actual structure of the building (like the hotel rooms) (Gibb, 1999; Goodier and Gibb, 2007).

Figure 2 presents the four aforementioned classifications along with their definitions, subcategories, typical materials and examples.

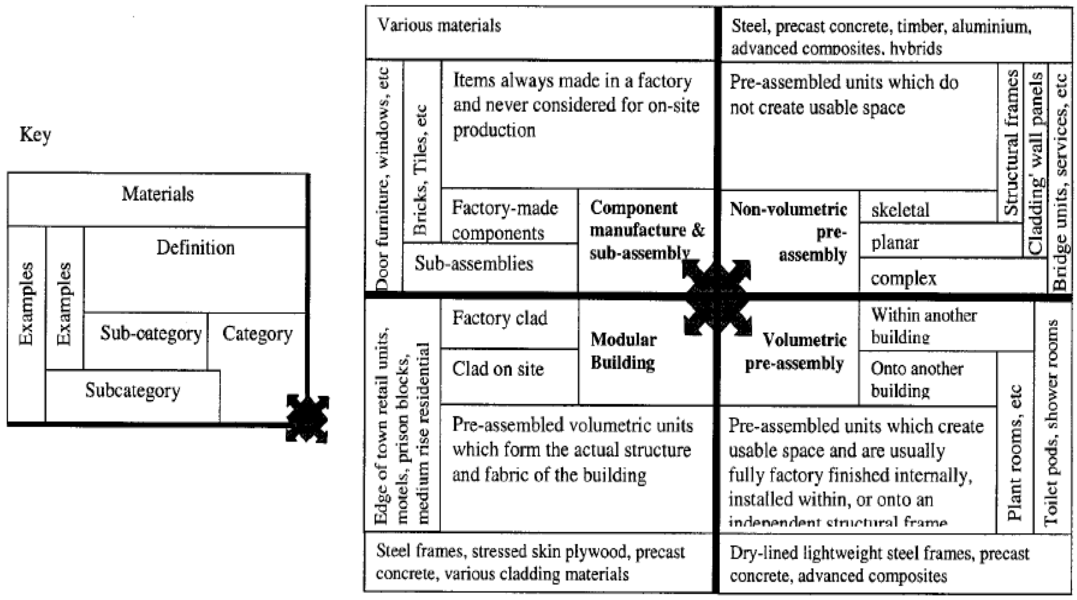

Figure 2 - Off-site construction categories (Gibb and Goodier, 2007)

Based on the previous literature and the search in the off-site construction market, it can be summarized the available components, in Lebanon and Syria, that classify under each off-site system (i.e. volumetric, hybrid, penalized, natural materials, and sub-assembly systems), as shown in Table 1.

Table 1 - Off-site systems and components in Lebanon and Syria

	Systems	Components
Off-Site Construction (OSC)	Sub-Assembly Systems	Precast Concrete Frames
		Precast Concrete Slabs
		Pre-Fabricated Foundations
		Floor and Roof Cassettes
	Panelized Systems	Light-weight Steel Open Panels
		Light-weight Steel Closed Panels
		Precast Concrete Panels
		Light-weight Composite Solid Precast Sandwich Panels
		Sandwich Steel Panels
	Natural Materials Systems	Open Panel Timber Frames
		Closed Panel Timber Frames
		Cross Laminated Timber (CLT)
		Structural Insulated Panels (SIPS)
	Volumetric Systems	Modular Construction
		Pod Construction
	Hybrid Systems	Semi-Volumetric Construction

2.2 The advantages and disadvantages of utilizing off-site construction

Although, off-site construction has huge advantages, using this method is still limited because of its potential downsides. For example, the marked share of off-site industry was only about 2-3% of the total buildings for new single family in the USA during the period from 2000 to 2014 (USCB, 2016). This percentage was low due to the misunderstanding that construction practitioners (architects, engineers, contractors, and clients) had regarding the huge advantages of the off-site method more than offset the disadvantages (Pasquire et al., 2002). Therefore, the construction practitioners should be educated on off-site benefits and drawbacks (Polat, 2010). The following sections explain the advantages and disadvantages that are offered by employing off-site construction in detail.

Off-site method leads to huge benefits in environmental and economic aspects:

1. **Time:** The productivity of the off-site method is higher than the on-site method due to: minimization the effects of extreme weather, reduction in the time lag between the on-site trades, and the performance of the activities in parallel rather than in sequence. Therefore, the use of off-site method has reduced construction time up to 60% as compared to the on-site strategy (Pasquire et al., 2006; Shen et al., 2014). Besides that, off-site construction is the best solution to deliver the building on schedule. For instance, Zenga and Javor (2008) stated that the total time to deliver off-site building was only four months, while a similar on-site building needed about 14 months. The off-site method offers not only fast completion, but also similarly reduces the design time from 21 months to 10 months.
2. **Cost:** According to the research done by the Construction Industry Institute (CII), the total cost saved was about 10% specially the on-site labor cost was reduced to 25%,

by using the off-site method (Na, 2007). These savings can be obtained by: manufacturing numerous components, ordering the materials in huge bulk, reducing the labor and machinery transportation, decreasing the construction time, reducing the on-site overhead, increasing the efficiency of energy and standardizing the design (Schoenborn 2012; Haas et al., 2002; Chan et al., 2006). Also, the off-site construction can reduce the number of workers on site that is reflected in the final cost of project (Haas et al., 2000).

3. **Safety:** Lawson et al. (2012) stated that the construction accidents could be reduced by 80% throughout employing the off-site technology. The off-site activities are considered as a safer than others because of reducing dangerous actions and workplace accidents, and avoiding the work at height and the effects of the bad weather. These reductions can be obtained by transforming the construction works to the factory environment (Na, 2007).

4. **Quality:** The controlled manufacturing facilities and high-tech off-site machinery can result in higher durability and quality for the off-site products (Neville, 2005; Hamill et al., 2006). Also, off-site manufacturing has reduced the exposure of materials to the on-site harsh weather, which contributes for finishing a building with better quality. Moreover, the off-site technology has improved the modularization and standardization of the building parts which leads to the better appearance of the building architectural (Kale and Arditi, 2006; Manrique et al., 2007; Soentanto et al., 2007). Lastly, the repetitive tasks in the factory environment educate the off-site workers to be more skilled and that leads to minimize the building defects (Chiu et al., 2012; Haas et al., 2002).

5. **Waste:** McGraw-Hill Construction stated that most of the off-site studies have emphasized that using off-site method result in reducing the waste (2011). Less amount of off-site waste is obtained because of the off-site factory is considered as a control environment which allows for increasing the opportunity to recycle the materials, and rising the ability for precise: purchasing, planning and cutting of materials (Na, 2007; Zenga et al., 2008). Besides that, the off-site units can be disassembled and relocated to the other projects after the life cycle of the building instead of disposed them (Li et al., 2013; Musa et al., 2015).

Although off-site construction provides significant advantages, it also leads to several disadvantages:

1. **Difficulty in making change later:** off-site construction increases the interdependency of construction activities. Therefore, any later modification leads to complexity and costly change. Whereas, changes in an off-site design can hold up a wide variety of interrelated activities and accordingly a clear analysis is needed in advance during the design phase (Jaillon et al., 2010; Mayra et al., 1994; Celine et al., 2009; Mao et al., 2015).
2. **Project planning:** the need for intensive pre-project planning and engineering is a significant disadvantage for utilizing off-site method. The preplanning for off-site method is totally different and more complex from on-site method. Off-site method requires strategic considerations for transportation, assembly and installation the final building (O'Connor et al., 2016; O'Connor et al., 2016; O'Brien et al., 2000).
3. **Transportation restraints:** This is another major disadvantages in adopting off-site method. The transportation considerations will restrict the size, weight, and dimensions of off-site components (Wei et al., 2014). Therefore, the off-site team

must study the special conditions of traffic control, access to the site and transportation rules before undertaken any design step (Jameson, 2007; Boyd et al., 2013).

4. **Coordination and communication:** an extra engineering effort is needed in all stages of off-site construction from procurement to delivery in order to provide access to the necessary information. Therefore, it is essential to share the information immediately such as decisions, designs, transportation requirements, and schedules among all stakeholders (owners, engineers, designers, suppliers, and contractors) (Na, 2007; Rahman, 2013).
5. **High initial cost and area constraints:** a large amount of initial capital is needed in order to set up the suitable machinery in the off-site factory (Chiang et al., 2006). Therefore, local condition of economy must be considered in the decision making of the investment in off-site construction. Not only the higher initial cost is a major difficulty also the area constraints. In a region where labor is cheap, off-site construction wouldn't be the preferable solution. Also, the availability of experienced designers and engineers in off-site method in a region should be taken into account (Haas et al., 2002).

To sum up, the use of off-site method faces a lot of disadvantages: more complicated planning processes, hard to make any change later, and needed for more communication. However, off-site construction has provided significant advantages: higher speed of construction, better productivity, cost savings, higher safety, higher quality, and less waste. In this regard, these advantages and disadvantages should be clearly defined and weighted by using environmental and economic criteria to decide if the off-site systems and components are appropriate for each given project (Kamali et al., 2016).

2.3 Decision support system

The purpose of this section is to highlight the decision support systems available in the construction industry in general to focus on off-site construction in particular. The section is broken down into two parts. First, a general discussion about the decision making process. Second, a detailed study of the decision making process in the construction industry as related to off-site construction.

2.3.1 Review of the decision support systems in the construction

Decision Support System (DSS) is a tool that assists the organizational decision-making for large variety of issues. Scott Morton (1971) stated the definition of DSS as: "interactive computer-based systems, which help decision makers utilize data and models to solve unstructured problems." DSS merges the capability of computers with human intellectual resources to enhance the quality of the decision. It can improve the decision making process and build a better understand of decision problem to lead the better results (Turban and Aronson, 2001).

The decision support system in construction was founded as a multi-attribute utility theory to support the construction practitioners in making decisions (Keeney and Raiffa, 1976). Then, DSS becomes a common tool in the field of engineering and construction. It assists the decision makers by integrating several sources of information from different system bases (Druzdzel and Flynn, 2002, Turskis et al., 2007). In addition, it increases the efficiency, effectiveness and productivity providing the optimal choice among several options.

There are several kinds of systems and models that have been designed for the construction industry in order to solve several complex decisions in the pre-project and pre-construction stages. At the beginning, Edwards (1977) developed a simplified multi-attribute rating technique (SMART) as a simpler decision support system. However, SMART was not able to support decisions with a long list of criteria. Then, the analytical hierarchy process (AHP) was developed by Saaty in order to structure the hierarchy problems and utilize the pairwise comparisons among different choices (1980). AHP has spread in several industries as an efficient tool; however, it needs an extra caution in identifying the decision rules. After this, the quality function development matrix (QFD) was created to integrate customers into the decision process (Sullivan, 1986). However, this matrix doesn't include numerical values to calculate the data, since it only uses '+' or '– 'as indicators. Then, choosing by advantages technology (CBA) was introduced to reach the objective of decision by comparing different choices (Suhr, 1993). Afterwards, the concept selection method (CSM) was proposed to facilitate the complicated selection decision by King and Sivaloganathan (1999). However, this method itself is a complex process. Lastly, the dynamic programming system (DP) was introduced to optimize the solution for complex problems by involving the user in establishing goals (Kulak, 2005). However, this tool is only applied for complex issues.

Most construction practitioners recommend the analytical hierarchy process method choosing by advantages technology due to their flexibility and simplicity, which lead to enhanced data collection and improvement in the quality of comparisons among the results (Pan et al., 2012). Therefore, this study will use AHP and CBA for assigning weight to each available decision.

2.3.2 Review of the decision support systems for selecting an off-site construction vs. an on-site construction

Most construction practitioners believe that the decision to employ the off-site method in construction projects is generally risky (Song et al., 2005; Kamali et al., 2017; Sacks et al., 2004; Tatum et al. 1987).

The decision whether to use off-site construction is considered as a multi-criteria decision making process. Hence, this issue can be solved only based on mathematical programming, simulation, and other statistical procedures, or artificial intelligence (Mitra, 1988). A decision to use off-site method should consider all the important factors: location, labor availability, and transportation. It also should define the customer objectives: minimizing cost and time. By considering this matter at the early design stage and allowing the engineers to evaluate and select the best method, a better-integrated project would be achieved (Sharafi et al., 2017). The following sections explore the most relevant studies conducted on decision support system on off-site construction in detail.

In 1993, Fisher et al. concentrated on the methodology of the decision making process to use the off-site method in a petrochemical factory. They provided a professional tool that was called MODEX. It is a computer system used by project managers and engineers, to run a detailed feasibility study during the conceptual stage of the project to choose between off-site and on-site construction. However, MODEX needed a few changes to become an effective decision making tool such as selecting the criteria based on the historical data of previous projects and adapting to other areas of the construction industry. Therefore, Song et al. enhanced this tool by updating the criteria according to the previous data, adding the risk analysis, and modifying it for different construction projects (2005).

Also, Fisher et al. improved MODEX tool by using neural network. The neutral network was built based on the data gathered from construction industry. This tool analyzed several factors: plant location, labor-related issues, project characteristics, and project risks to make a decision for using off-site manufacturing. However, using this tool required large amount of historical data, and assumed that the past modularization decisions were correct (1999).

Then, Gibb and Pendlebury (2006) developed a tool called CIRIA Toolkit to optimize the benefits of the off-site method. It consisted of several stages: choose drivers and constraints, rank drivers and constraints, review overall project off-site process strategy, select performance indicators, measure off-site benefits, determine the qualitative values of the specific benefit and develop strategy. However, the most significant challenge to use this tool is required the large amount of input data at an early stage of a project.

After this, Pan et al., (2008) designed a multi-criteria analysis for the house building projects that was called build system selection tool. This tool was intended to improve the selection of the construction methods at early design stage by establishing a decision making matrix. This matrix combined the weights or scores, examined the results, performed sensitivity analysis and monitored the findings. It created the success of decision making process based on practical criteria among the different alternative construction systems. However, it was not designed to compare the off-site versus on-site method into other construction facilities and other areas of the construction industry.

Furthermore, Chen et al. (2010) designed a transport tool to help engineers in making the decision to use the off-site method in the construction field. This tool was divided into two stages: the strategic and tactical level. Firstly, the simple multi-attribute rating technique (SMART) evaluated the preliminary feasibility study. Secondly, the multi-attribute utility theory (MAUT) involved the risk and uncertainty analysis. By dividing this analysis into two-stages, the decision makers can make an expedited decision. If decision-making problems are fairly simple, they can be solved during the first stage and the detailed assessment is not necessary. Therefore, this decision support system was considered as a useful tool. However, it was not integrated into the computer software, which is used to facilitate the evaluation process.

Pan et al. (2012) have worked on enhancing the decision criteria by validating their decision making tool to six large house buildings and five large firms in the UK. Their tool has included five stages to make a decision: illustrating the status of decision, defining the decision purpose, putting its criteria, clustering the criteria, and valuating these criteria. Moreover, it has stated 50 attributes for comparing between off-site and on-site construction. These attributes were classified into several groups: cost, quality, time, health and safety, process, sustainability, process, procurement, regulatory, and statutory acceptance. However, the sub criteria were not prescriptive and should be adapted to the project context concerned, whereas the establishing criteria should be generically applicable.

Some of the most relevant studies were conducted for applying the decision support systems on the off-site construction are summarized in Table 2.

Table 2 - Studies on the decision support system for off-site construction

Author(s)	Year	Summary	Limitations
Fisher et al.	1993	This study developed a DOS-based expert system (MODEX) to evaluate the feasibility analysis of OSC for a power plant project	DOS-based software would need to be updated to other areas of the construction industry
Fisher et al.	1997	Neuromodex was developed based on MODEX by using neural networks	Using Neuromodex requires the large amount of historical data, and assumes that the past modularization decisions were correct
Gibb and Pendlebury	2006	This study developed a tool called CIRIA Toolkit to optimize the benefits of the off-site method	The most significant challenge to use this toolkit is required the large amount of input data at an early stage of a project
Pan et al.	2008	This study has designed a multi-criteria analysis that was called build system selection tool	It was not designed to be compare the off-site versus on-site method into other construction facilities
Chen et al.	2010	This paper presented an objective and transparent tool to aid team members during early stages in evaluating the feasibility of prefabrication and exploring an optimal strategy to apply prefabrication in concrete buildings	This model needs further developed into a computer program, which is used to facilitate the evaluation process
Pan et al.	2012	This paper established decision criteria, structured in the form of a three-level decision matrix, for comparing off-site with conventional construction methods	The sub criteria were not prescriptive and should be adapted to the project context concerned, whereas the establishing criteria should be generically applicable

CHAPTER 3

RESEARCH MOTIVATION AND OBJECTIVES

3.1 Problem statement and motivation

Many researchers have benefitted from bringing the automotive manufacturing principles into construction by adopting various off-site systems and components. However, none has attributed careful attention to selecting the appropriate off-site system or component based on the practitioners' value maximization goals (i.e. cost, quality, etc.). For instance, clients typically allocate importance to either productivity, quality, safety or the project cost performance (Song et al., 2005). Therefore, there is a need to develop a decision making evaluation model that takes various stakeholders' goals into account to maximize the project value.

Resorting to off-site systems and components is very important to improve current construction methods. However, none of the previous works have maximized the benefits of using this technology (i.e. OSC) by optimally selecting the best off-site system or component. Therefore, another contribution of this research work lies in identifying the optimal off-site systems and components by creating a decision support system. This is achieved by resorting to analytical hierarchy process (AHP) and choosing by advantages (CBA) techniques.

Furthermore, some literature research studies have attempted at comparing off-site construction against on-site construction but none have performed a comparison among non-volumetric systems (e.g. Panelized and Natural materials), volumetric systems and hybrid systems. Moreover, no comparison was carried out among each system components. Accordingly, this research work comparatively assesses the various off-site systems and components.

Other studies have focused on different types of OSC but none has considered or extensively researched the various systems and components' attributes to highlight their difference. In fact, each off-site component presents different advantages and disadvantages, although they belong to the same system. Therefore, in the present study, the attributes of the different systems and components are extracted and analyzed in detail.

3.2 Research objectives

The overall objective of this research effort is to design and develop a multi-criteria decision making tool for selecting the most appropriate off-site system and component to be adopted on construction projects in Lebanon and Syria while taking the different goals of owners and users (e.g., cost minimization, better safety, etc.) into account.

Accordingly, the model is divided into two sequential levels whereby: (1) the analytical hierarchy process technique (AHP) is used in the first level for preliminary selection among Panelized, Natural Materials, Volumetric and Hybrid Systems, and (2) the choosing by advantages theory (CBA) is employed at the second level to consider the attributes of the chosen methods.

To achieve the overall objective, six interim objectives were identified as follows:

1. Investigate and analyze the characteristics and attributes of the different off-site systems and components in the construction industry.

2. Review the decision support systems that are currently being used to choose between off-site and on-site methods adoption in the construction industry.
3. Identify the existing off-site systems and components which are used in both countries, Lebanon and Syria.
4. Identify the critical factors needed at the evaluation stage for effectively selecting a suitable off-site system and components.
5. Develop and test the decision model that assesses and compares the four categories of off-site systems (i.e. Panelized, Natural Materials, Volumetric and Hybrid Systems).
6. Apply the choosing by advantages method for comparing among the off-site components that can be strategically utilized on construction jobsites in Lebanon and Syria, following the decision maker's objectives (e.g. cost minimization, better safety records, etc.).

3.3 Research questions

The broad question that this research is trying to answer revolves around the main objective of the project (e.g. cost minimization, better safety records, etc.); how does a decision maker decide on the appropriate off-site system and component to be utilized on construction projects in Lebanon and Syria?

However, this research focuses on two less general questions for the purpose of this research: (1) How can the proposed framework facilitate the decision making process that needs to be followed to choose among off-site systems and components? And (2) what are the main critical factors that will affect the decision in choosing the best off-site system and component?

CHAPTER 4

RESEARCH METHODOLOGY AND METHODS

A research methodology is created to answer the study research questions. This methodology is presented in Figure 3 which includes the main tasks: 1) Background investigation, 2) Application of the DSS through the AHP technique, 3) Application of the DSS through the CBA technique. The following sections describe the methodology that is followed in detail.

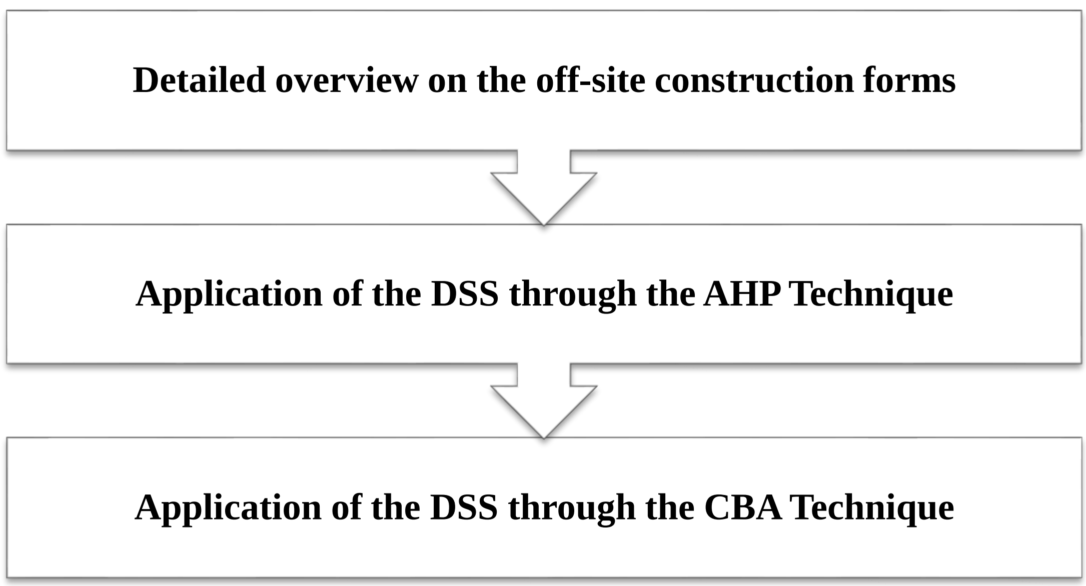

Figure 3 – Research methodology

The flow chart of decision support system for choosing between off-site and on-site construction, and among different off-site systems and components is described in Figure 4.

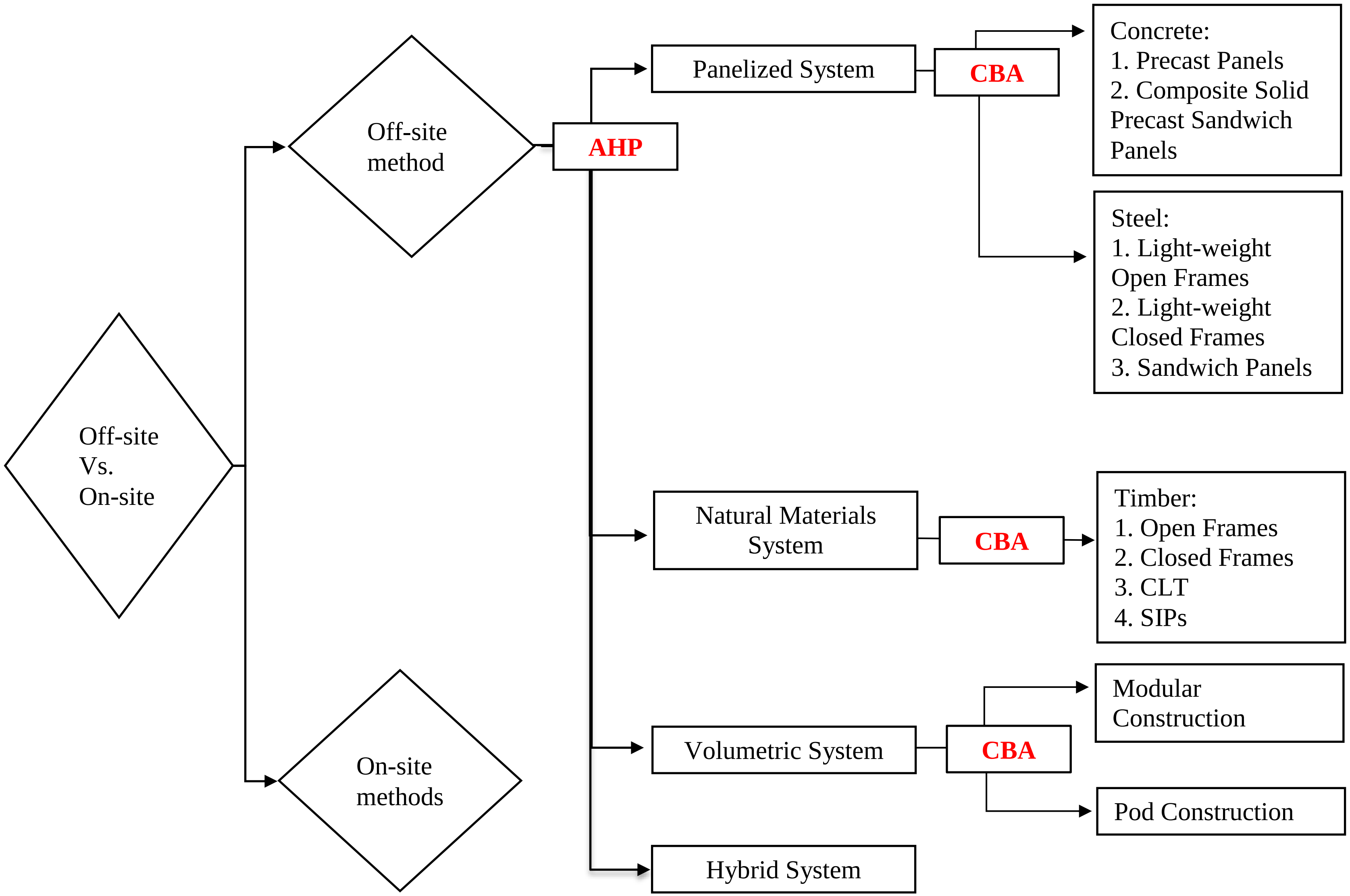

Figure 4 - The flow chart of decision support system for choosing between off-site and on-site construction

4.1 Detailed overview on the various forms of off-site construction

In order to gather the attributes of the off-site systems and components, a thorough search in the manufacturing market of Lebanon and Syria was conducted. Then, a classification of these attributes into different categories (design, cost, time, durability, safety, energy, quality, environment, waste, treatment, maintenance and others) was performed. This classification process is as a useful tool to show the differences among all off-site systems and components and therefore explain how the decision would change according to the project's objectives.

4.2 Application of the decision support system through the analytic hierarchy process (AHP) technique

For the purpose of creating the first step of the evaluation process, a conceptual decision model was developed based on the literature review and primary regional data. This model was designed and tested for assigning the weights to the four off-site categories (i.e. Panelized, Natural Materials, Volumetric and Hybrid Systems) for building projects. The analytic hierarchy process (AHP) was used to establish the weights.

After having designed the AHP model, the next step involved conducting it with a selection of senior managers from top off-site builders in Lebanon and Syria. A total of 24 off-site builders participated in this survey, whereby most of them have more than 5 years of experience in this field. A pairwise comparison was performed with respect to the cost, time, quality, health and safety, sustainability and process criteria. Also, the ranks of importance for one criterion over the other were established based on the scale system, as introduced by Saaty (1980).

4.3 Application of the decision support system through the choosing by advantages (CBA) technique

For the purpose of building the second stage of the evaluation process, another decision support system was used after selecting one of the off-site systems (i.e. Panelized, Natural Materials, Volumetric and Hybrid Systems). The alternative decision tool, the choosing by advantages (CBA), assists in the selection of the appropriate off-site component, based on the decision maker's objectives (e.g. cost minimization, better safety records, etc.). 34 objectives were considered in the CBA case study to select the most suitable off-site component. A total of 24 off-site construction stakeholders participated in filling the CBA case study. The effect of each factor in choosing the most suitable off-site component was discussed and the differences among different construction stakeholders were highlighted.

CHAPTER 5

FORMS OF OFF-SITE CONSTRUCTION

5.1 Sub-assembly systems

Sub-assembly units are the building elements which are produced at off-site location before being transported to the site in order to be lastingly created. These elements are considered as small parts of a building like roof trusses, precast concrete frames and hollow care slabs. Moreover, these components can be combined into either off-site construction or on-site construction dwellings. However, these units are not form the full building system. There are many different types of sub-assembly systems which are employed world-wide. However, the main types used in Lebanon and Syria are:

1. **Precast Concrete Frame:** This component includes beams and columns which can be manufactured in the factory with different sizes for transport and assembly at the site.

Figure 5 – Precast concrete frames (Hashemi et al., 2016)

2. **Precast Concrete Slab:** The precast slab produced outside the site is typically used in the construction of floors in multi-story buildings for better control quality and reduction the waiting time of days for the concrete to set and cure. Since the

precast unit is prepared in the off-site factory, transported and assembled on-site with no delay.

Figure 6 –Precast concrete slabs (Hashemi et al., 2016)

3. **Precast Concrete Foundations:** The precast foundation is built off-site in the controlled environments and then transported to be assembled in the project site. When the units are produced off-site is higher strength even though it is thinner and lighter.

Figure 7 – Precast concrete foundations (Hashemi et al., 2016)

4. **Floor and Roof Cassettes:** The precast floor is produced to construct a floor or sloped roof of the building. It reduces the number of workers and minimizes the risks of working at height. Using this kind of roof permits the construction to

become watertight more quickly than with conventional trussed rafter or cut roof constructions.

Figure 8 –Floor and roof cassettes (Hashemi et al., 2016)

The attributes of sub-assembly components in Lebanon and Syria are presented in Table 3.

Table 3 – The attributes for the sub-assembly components

System	Components	Attributes										
		Design	Cost	Time	Durability	Safety	Energy	Quality	Waste	Treatment	Maintenance	Others
Sub-Assembly Systems	Frames	Carefully consideration for the connections among units.	Joints are expensive.	Quick assembly.	*High strength. *Need lighter foundations	Improve safety on site.	Energy savings.	High quality.	Reduce material wastage.	Units may be damaged during transport.	Need maintenance.	*Elimination of temporary structure. *Very heavy members.
	Slabs	Long spans at thin sections.	More economical.	Quick to build.	Achieve structural efficiency.	Reduce the risk of working at height.	Energy savings.	Good quality control.	Materials can be recycled.	Need to treat for rust.	Need maintenance.	*Elimination of temporary structure. *Easy to extend.
	Foundations	Carefully consideration for the connections between units.	Cost-effective.	Short installation time.	High load-bearing capacity.	Reduce the risk at on-site.	Elements can be reuse.	Good quality control.	Elements can be reuse	Units may be damaged during transport.	Don't need maintenance.	*Very heavy members. *Need moisture protection coating
	Cassettes	Utilize the whole loft space to create a larger living area.	Economical units.	*Fast completion. *load sequentially to speed up erection.	Robust details.	Reduce the risk of working at height.	Increased energy performance.	Higher degree of quality.	Less waste material on site.	Need to treat for rust.	Don't need maintenance.	Can be transported to another location anytime.

5.2 Panelized systems

The panelized units are produced in the factory and then are transported to project site in order to fit within the three-dimensional structure or assembly into existing structure systems. These units can be wall, floor and roof panels to produce the complete structural shell. These panel units can be load-bearing (i.e. providing structural support) or non-load-bearing. They can be made of light gauge steel, timber, structurally insulated panels (SIPs) or concrete, which are used to create the whole building. There are several types of panelized systems which are employed world-wide. However, the main types used in Lebanon and Syria are:

1. **Lightweight Steel Open Panels:** Panels are delivered to site where they are fitted with insulation, windows, services and linings. All components of open panel structural are visible. This method can be utilized as non-structural walls, partitions or panels to transmit the loads to the foundations.

Figure 9 – Lightweight steel open panels (Hashemi et al., 2016)

2. **Lightweight Steel Closed Panels:** The structural framing panels are delivered to site with previously factory installed windows, doors, services, internal wall finishes and external cladding. The internal structural components can only be

seen around the perimeter of the panels. The trade-off is between the open and closed panel an increase in factory-work but a decrease on-site work.

Figure 10 –Lightweight steel closed panels (Hashemi et al., 2016)

3. **Precast Concrete Panels:** The concrete panel is cast in a reusable form at a controlled environment. Since the precast panel is produced in the off-site factory, transported and assembled on-site with no delay.

Figure 11 –Precast concrete panels (Hashemi et al., 2016)

4. **Light-weight composite solid precast sandwich panel:** This panel consists of two layers of reinforced concrete separated by an interior void held together with embedded steel trusses.

Figure 12 – Light-weight composite solid precast sandwich panels (Hashemi et al., 2016)

5. **Sandwich Steel Panels:** The sandwich panel consists of a metal outer skin, bonded to an insulation board forming its core. It is used for roof and wall applications.

Figure 13 –Sandwich steel panels (Hashemi et al., 2016)

The attributes of panelized components in Lebanon and Syria are presented in Table 4.

Table 4 – The attributes for the panelized components

System	Components	Design	Cost	Time	Durability	Safety	Energy	Quality	waste	Treatment	Maintenance	Others
Panelized Systems	Precast Concrete	*Design flexibility. *Different finishing solutions.	Improved profitability.	Longer time for erection with complicated material management on site.	Superior strength and durability.	Earthquake and fire resistance.	Energy savings.	*Consistent quality. *Robust Form.	Site efficiency.	Hard surface resistance to damage during construction.	Low maintenance.	*Availability on market. *Need high level of logistics.
	Composite Solid	*More complicated design process. *Different finishing solutions.	Reduce costs for erection and structural support.	Time savings.	Flexural strength.	Fire resistance.	*Insulation provides. *Superior energy performance and moisture protection.	Highly quality product.	Reducing waste.	Units may be damaged during transport.	Need maintenance.	Requires skilled labors.
	Sandwich Steel	*Being light in weight. *Flexible. *Water proof. *Curved structure.	*Cost effective	Rapid fabrication and installation.	Low level of durability.	Decreasing risks.	Thermal efficiency.	Good quality.	Minimum material use.	Coated, hygienic surfaces that can be washed down frequently.	Low maintenance.	*Noise elimination. *Less handling on site.

System	Components	Attributes										
		Design	Cost	Time	Durability	Safety	Energy	Quality	waste	Treatment	Maintenance	Others
Panelized Systems	Light-weight Steel Panels	Versatile.	Expensive.	*Build faster with steel. *Connection may easy.	*Steel is lighter than wood. *Strong.	Fire resistance	Excellent thermal performance	Stable material.	Reuse of components.	Require added insulation.	Less Maintenance	Light weight for using on poor ground
		Open Frame	Design and manufacturing errors are less costly to rectify.	Take more work offsite. **Design**: On site modification may be easier. *Less design input.	*Light steel framing is used for the primary structure of housing. *Steel's inherent strength.	Earthquake and fire resistance.	Less energy efficiency.	Accuracy.	All steel products are recyclable.	Normally being non-insulated.	Less Maintenance	* Can easily be extended or modified. * All structural components are visible.
		Closed Frame	Design and manufacturing errors are costly to rectify.	Less time is spent on site. **Design:** On site modification may be harder. *More design input.	*Frame vulnerable to damage during transport and installation. *Joints are more complex.	Earthquake and fire resistance.	More energy Efficiency.	Leads to higher quality dry envelope.	Reduce the waste on site.	Being insulated.	More Maintenance	* Structural components can only be seen around perimeter of the panel.

5.3 Natural materials systems

Natural materials systems are similar to panelized systems with one difference; the source of materials means that making the selection of the natural materials systems are more environmental sustainability than other systems. There are several types of natural materials systems which are employed world-wide. However, the main types used in Lebanon and Syria are:

1. **Open Panel Timber Frame:** Framed structures of heavy timber are produced off-site and jointed together. This frame is delivered open without windows and doors, electrical, plumbing and insulation which are assembled at on-site. To prevent the movement of structural vertical beams or racking, diagonal bracing is used.

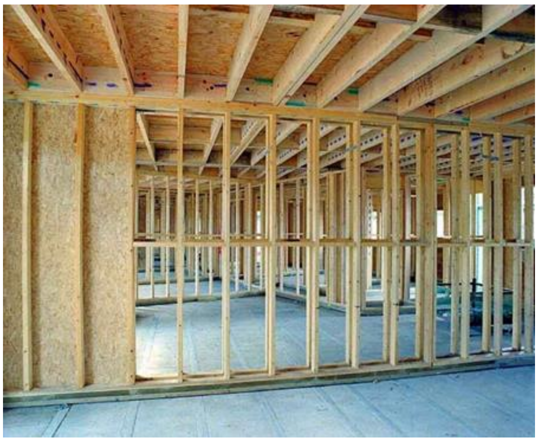

Figure 14 – Open panel timber frames (Hashemi et al., 2016)

2. **Closed Panel Timber Frame:** This frame for both external and internal walls is manufactured in the off-site location complete with windows and door. The trade-off is between the open and closed panel an increase in factory-work but a decrease on-site work.

Figure 15 – Closed panel timber frames (Hashemi et al., 2016)

3. **Cross Laminated Timber (CLT):** It means a timber panel produced from gluing layers of solid-sawn lumber together. Each layer of board is orientated perpendicular to adjacent layers for strength and glued on the wide faces of each board, usually in a symmetric pattern so that the outer layers have the same orientation.

Figure 16 – Cross laminated timber (CLT) (Hashemi et al., 2016)

4. **Structural insulated panels (SIPS):** These panels comprise two layers of sheet material bonded to a foam insulation core. The panel also consists of structural core of insulation which is glue-bonded on each face to a racking board; the materials for the board vary with manufacturers but typically are plywood.

Figure 17 – Structural insulated panels (SIPS) (Hashemi et al., 2016)

The attributes of natural materials components in Lebanon and Syria are presented in Table 5.

Table 5 – The attributes for the natural materials components

System	Components	Design	Cost	Time	Durability	Safety	Energy	Quality	waste	Treatment	Others
		Attributes									
Natural Materials Systems	Open Panel	*Less design input. *Design errors are less costly to rectify.	*Cost effective. *Greater levels of labor required on site.	* More time is spent at on-site. * Easy to transport and disassemble.	Robustness.	Less safety than closed panel.	Thermal performance.	High quality.	Reduce waste (19.16m3 of waste generated per 100m2 of floor area).	Damage easily repaired.	Frame vulnerable to abuse by other trades after erection.
	Closed Panel	*More design input. *Design errors are costly to rectify.	*Higher costs.	*Less time is spent on site.	Strong and durable.	Reduced the risk on the site.	*Higher level of Insulation. *Better energy efficiency.	Higher quality	Can be built from recyclable materials.	Damage and errors aren't cheaper and easier to rectify.	*Complexity in jointing. *Lower levels of labor required on site.
	CLT	Design flexibility.	Cost competitiveness	Speed installation.	Robust solid wood system.	*Fire protection *Seismic performance.	Thermal and energy efficiency.	High quality.	Resource efficiency.	Don't need a treatment.	Material can be easily shaped and modified.
	SIP	Flexible design.	* More expensive solution. Reduce heating and cooling cost.	High speed build.	Provide a stronger building structure.	Improved safety.	Excellent insulation performance.	Making an excellent end-product.	Less waste (16.84m3 of waste generated per 100m2 of floor area).	Don't need a treatment.	Can be more readily sourced in a wider range of structural sizes and strengths.

5.4 Volumetric systems

3-D modules factory are produced with high quality control, then transported to the project site to be assembled by bolted technology. The structural skeleton of modules will usually be concrete, light gauge steel, timber frame or composite with different external and internal finish materials. They can be brought to the project site in different forms. The modules can be as complex as including required external and internal finishes or as a simple basic structural shell.

These systems are most efficient when used for large quantity of module units. For example, about four units plus roof are needed for prefabricated house. However, the one-unit apartment is inefficient use of volumetric systems.

Volumetric systems have two components, which are employed in Lebanon and Syria:

1. **Modular Construction:** The pre-engineered building units are produced in the factory, then they are delivered to site and assembled as substantial elements of building or as large volumetric components.

Figure 18 – Placing of volumetric units to complete block of flats (Hashemi et al., 2016)

2. **Pod Construction:** This component was first developed in the construction market for student accommodation and hotels. A pod is a non-structural module and is used

within the loadbearing structure. It is fabricated as a 3-D unit fitted with all equipment services and assembled on-site within the superstructure of a building.

Figure 19 – Bathroom pods (Hashemi et al., 2016)

The attributes for the volumetric components in Lebanon and Syria are presented below in Table 6.

Table 6 – The attributes for the volumetric components

System	Components	Attributes										
		Design	Cost	Time	Durability	Safety	Energy	Quality	Waste	Treatment	Maintenance	Other
Volumetric Systems	Modular Construction	Less flexible (any late design changes will be costly).	*Most expensive offsite solution when used for small number of module units.	Reduce schedule by maximizing work completed at off-site.	Connection between units must be carefully considered.	Improved safety.	Use Less energy.	*Ensure units are inspected at on-site. *Maximize quality.	*100 percent recyclable. *Less materials waste (5.51m3 of waste generated per 100m2 of floor area).	Don't need a treatment.	Low maintenance	*Logistics is necessary *Solution to overcome site resource constraints. *Additional construction effort.
	Pod Construction	Ensure that matching doors and furniture with the rest of the dwelling.	Substantial repetition is required to ensure pods are cost competitive with conventional methods.	Take more work offsite and less time is spent on site.	Ease of connection to the rest of building.	Safer work on site.	Reduced material requirements and increased material recyclability.	Good quality.	*Can be recycled. *Minimum waste.	Need to protect from the weather till the rest of the structure is being built	*Easy access to the services *Ensure access to services for maintenance within the pod.	Easy to transport.

5.5 Hybrid systems

The hybrid units combine both panelized (2-D approach) and volumetric (3-D approach) technology together in the same construction. They are called semi-volumetric units. These units construct the highly serviced area as volumetric units (such as kitchen or bathroom units) and the rest of the dwellings are built as panelized units.

Figure 20 - Semi-volumetric construction (Hashemi et al., 2016)

The attributes of the hybrid components are presented in Table 7.

Table 7 - The attributes for the hybrid components

System	Components	Attributes								
		Design	Cost	Time	Safety	Quality	Environment	Waste	Maintenance	Others
Hybrid Systems	Semi-Volumetric Construction	*Consideration for the materials at the interface between the volumetric and panelized units. *Require an early agreement on specifications. *Panelized units increases flexibility of layout.	Minimum labor cost.	High productivity.	Reduce the potential for accidents by decreasing the on-site work.	Combine the best quality elements of volumetric and panelized units.	Sustainable building in minimum time.	Efficient use of materials.	Ensure access to services for maintenance.	*More coordination if different manufacturers' products are being used. *Provide a chance of having conflicts between corporate manufacturers. *Ease of transportation.

CHAPTER 6

DEVELOPMENT OF THE DECISION SUPPORT SYSTEM

6.1 Analytical hierarchy process (AHP) model

6.1.1 AHP definition

In order to accomplish the first stage of evaluation, a conceptual decision model was initially developed using the combined key findings gathered from the literature review and regional data. At the heart of this model lies various off-site building categories (i.e. Panelized, Natural Materials, Volumetric and Hybrid Systems) for which weights are to be allocated using the Analytic Hierarchy Process (AHP) method.

The analytic hierarchy process (AHP) theory has been utilized to investigate and evaluate multi-criteria decisions in the construction industry for a range of problems (Turskis et al., 2009; Larorre and Riley, 2010; Vaidya and Kumar, 2006). AHP was developed in 1980 by Thomas Saaty, as an advanced, and flexible tool to deal with complexity of the decision making process, to calculate the weights for each alternative following pairwise evaluations of the criteria introduced by decision makers, and to prioritize the criteria. It combines the objective and subjective aspects of a decision and builds the complexity, measurement, and synthesis of decision alternatives (Forman and Gass, 2001). Through applying the AHP analysis, hierarchies are first settled. After that, decisions regarding comparing alternatives are established with respect to a set of criteria related to the same problem and weights are then given. Finally, it checks the consistency of the decision maker’s evaluations in order to decrease the bias in the decision making process. This method transfers the qualitative and quantitative analysis into multi-criteria ranking. In a very simple manner; decision makers can easily fill out the survey without having previous background or experience with AHP. To reach an accurate decision in the AHP, the steps below should be followed:

a. State the decision problem.

b. Establish the purpose or goal behind a certain decision.

c. Determine the main criteria with respect to the decision goal.

d. Determine the adaptation options.

e. Build a group of pair-wise comparison matrices.

f. Collect all the pairwise comparison data.

g. Compute the importance and weight for each alternative option.

In this study, the analytical hierarchy analysis that was adopted is presented in Figure 21.

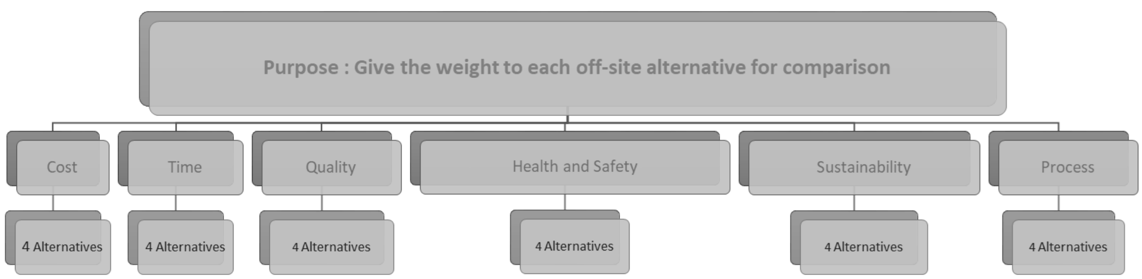

Figure 21 - The proposed analytical hierarchy analysis/model

As shown in Figure 21, this study focuses on six specific criteria in the AHP evaluation, namely:

1. **Cost:** the cost of design, implementation and maintenance.

2. **Time:** the time of design and implementation.

3. **Quality:** high quality achieved in erecting the facility and high customers' satisfaction.

4. **Health and safety:** risk minimization during the construction process.
5. **Sustainability:** high building energy efficiency and waste minimization.
6. **Process:** project site access, logistics, and installation planning strategies.

Moreover, the four alternatives adopted in the AHP analysis are off-site construction categories that were identified, based on regional and local needs, as follows:

1. **Non-Volumetric Panelized Systems:** These units are produced in the plant then transported to the project site to fit within the assembly into existing structural systems. Examples include wall, floor or roof panels that can be load or non-load-bearing and can be made of light gauge steel, timber, structurally insulated panels (SIPs) or concrete.
2. **Non- Volumetric Natural Materials Systems:** These units are similar to the panelized systems with one difference: the source of materials. This difference leads to the consideration of natural materials systems that are more environmentally friendly and sustainable than other systems.
3. **Volumetric Systems:** These units are produced with high quality control then transported to the project site to be assembled through bolting. The structural skeleton of these modules are usually fabricated with concrete, light gauge steel, timber frame, or composite with different external and internal finishes materials.
4. **Hybrid Systems:** These units (called semi-volumetric units) combine panelized and volumetric technology in the same constructed facility or building. The highly serviced areas of a building (e.g. kitchen, bathroom units, etc.) are constructed as volumetric units while others are built as panelized units.

6.1.2 Implementation of the AHP survey

After having designed the AHP conceptual model, the next step involved designing the AHP survey then conducting it with a selection of senior managers from top off-site builders in Lebanon and Syria. The AHP survey was conducted to obtain the full range of managers' opinions and illustrate the effect of the different factors used on the choice of off-site options.

The AHP survey was divided into three sections: (1) A cover letter to the participant including the invitation, (2) A brief summary of the research topic including the goal of the survey, and chosen criteria and alternatives, and (3) The scale system (Table 8) as introduced by Saaty (1980).

Table 8 - The AHP pairwise comparison scale (Saaty, 1980)

Intensity of weight	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objectives
3	Weak/moderate importance of one over another	Experience and judgment slightly favored one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent scale values	Used to represent compromise between the priorities listed above

Also, the third section of AHP survey includes: a small example on how two criteria can be evaluated and ranked, the general questions about the type of systems adopted in the interviewed companies, the pairwise comparison with respect to the cost, time, quality, health and safety, sustainability and process criteria and the pairwise comparison for one criterion with respect to other criteria. The AHP survey was done by conducting semi-structured interviews with construction managers and explaining the necessary terms and assumptions.

6.2 Choosing by advantages (CBA) model

6.2.1 CBA definition

In order to achieve the final objective, another technique has been used after selecting one of the four off-site categories (i.e. Panelized, Natural Materials, Volumetric and Hybrid Systems). This technique, the choosing by advantages (CBA), is used to select an appropriate off-site component, based on the decision maker's objectives (e.g. cost minimization, better safety records, etc.).

The CBA technique is a decision-making method introduced by Jim Suhr (1999). It assists the users in reaching the best decision by comparing different choices. It is labeled as a useful tool because "people suffer the consequences of unsound decisions. They mask the causes by attributing them to human imperfection, natural probability or uncontrollable events." (Koga, 2008). Using this tool in a correct way leads to better decisions. Therefore, it is very important to define the important terms in the CBA analysis:

- **“Alternative is a possible decision.”** (Parish and Tommelein, 2009). The CBA method aids the users to decide among certain choices which are considered as alternatives.
- **“Factor is a container for criteria, attributes, advantages, importance and other types of data”** (Suhr, 1999). It is important to carefully identify all possible factors which can affect the decision in every step of the CBA analysis. Otherwise, it leads to a wrong decision.
- **“Criterion is a decision rule or guideline established by the decision-maker.”** (Parish and Tommelein, 2009), which means that every analysis needs a specific objective defined by the users.
- **“Attribute is a characteristic, quality or consequence of one alternative.”** (Parish and Tommelein, 2009). Each alternative comes with attributes.
- **“Advantage is a beneficial difference between two and only two attributes.”** (Parish and Tommelein, 2009). Each decision must be made according to the differences between two attributes.

In this research, CBA is used in the following manner:

1. **Defining the factors:** This is the most crucial step. Careful consideration by the decision makers is needed, to include all factors that affect the analysis.
2. **Defining the criteria for each factor:** The decision maker should set the limits for the factor’s characteristics.
3. **Defining the attributes of each alternative:** A rather simple process, where the decision maker figures out the properties of each alternative.

4. **Determining the advantages of each alternative:** The user should compare each alternative with the proposed criteria and contrast two alternatives at a time. As a result, the weakest alternative must be defined, which has zero advantage, and then the other alternatives must be compared with it, to identify their advantages.

5. **Assigning the importance of each alternative:** The user assigns weights for the alternatives to evaluate the advantages of each and identify the most important one.

6. **Selecting the alternative with highest grade:** The decision maker adds up all the importance scores for each alternative and decides which option is more beneficial to use.

The second stage for selecting the suitable components is presented in Figure 22.

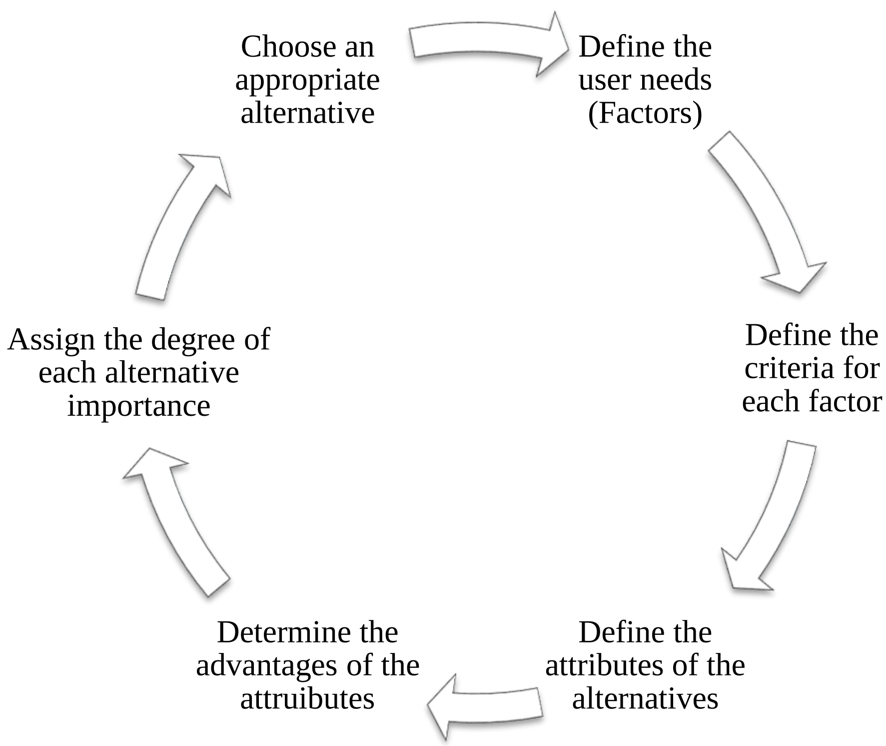

Figure 22 - The second stage of decision making process in selecting of the suitable off-site components

6.2.2 Case study: the studio building at the American University of Beirut

The studio building is a 600 m^2 off-site project that was constructed this year at the American University of Beirut (AUB) in Beirut, Lebanon for the architectural and graphic design students (Figure 23). Each story consists of a big studio, one office, one kitchen and two bathrooms. This building was taken as a case study in this research because it represents a typical steel off-site building in Lebanon. The question that the CBA tool addressed revolves around the main objective of the project (e.g. cost minimization, better safety, etc.); how does a decision maker decide on the appropriate off-site component to be utilized on construction projects in Lebanon and Syria?

Figure 23 - Studio building at the American University of Beirut

6.2.3 Defining the off-site options and the established factors

The next step involves categorizing the established 34 factors into seven groups as follows:

1. **Design and Execution:** the amount of design input, design flexibility, finishes solutions, design process, design connections, ability to alter on-site, thermal protection solutions, fire resistance and earthquake resistance.
2. **Quality:** high quality achieved in erecting the building, high customers' satisfaction, more robust and durable facility, and great building appearance and aesthetics.
3. **Health and Safety:** minimization of the on-site risk and the need of the on-site safety requirements.
4. **Sustainability:** high building energy efficiency, energy savings, on-site solid waste e minimization, water reduction, off-site components reused and LEED certification achievement.
5. **Cost:** the cost of design, maintenance, off-site components, heating and cooling energy as well as additional rework cost due to design or manufacturing errors.
6. **Time:** the duration of the design process, installation and assembly, work coordination and the overall construction time.
7. **Process:** the need for logistics, planning of installation and possibility of damage during transport.

Furthermore, five available adaptation options which are available as panelized components in Lebanon and Syria were considered:

1. **Precast Concrete Panels:** The concrete panel is cast in a reusable form at a controlled environment. Since the precast panel is produced in the off-site factory, transported and assembled on-site with no delay.
2. **Light-weight Composite Solid Precast Sandwich Panels:** This panel consists of two layers of reinforced concrete separated by an interior void held together with embedded steel trusses.
3. **Light-weight Steel Open Panels:** Panels are delivered to site where they are fitted with insulation, windows, services and linings. All components of open panel structural are visible. This method can be utilized as non-structural walls, partitions or panels to transmit the loads to the foundations.
4. **Light-weight Steel Closed Panels:** The structural framing panels are delivered to site with previously factory installed windows, doors, services, internal wall finishes and external cladding. The internal structural components can only be seen around the perimeter of the panels. The trade-off is between the open and closed panel an increase in factory-work but a decrease on-site work.
5. **Sandwich Steel Panels:** The sandwich panel consists of a metal outer skin, bonded to an insulation board forming its core. It is used for roof and wall applications.

To sum up, this methodology was established to be an initial analysis tool. Moreover, the 34 factors were established to highlight the most significant ones used in the selection process. In addition, inaccurately selecting factors would lead to a wrong decision regarding off-site options. Therefore, this method guides decision makers to focus only on the difference among off-site options according to important factors instead of wasting time on ill-defined factors or unclear problems.

6.2.4 Proposed CBA framework

The proposed CBA framework is presented below in Table 9.

Table 9 - The proposed CBA framework

Factors		Option 1	Option 2	Option 3	Option 4	Option 5
		Precast Concrete Panels	Composite Solid Precast Sandwich Panels	Light Weight Steel Open Panels	Light Weight Steel Closed Panels	Sandwich Steel panels
Design and Execution						
1	Design Input					
Criteria	Minimal amount of design information is desirable					
Attribute						
advantage						
2	Design Flexibility					
Criteria	Ability to changes at a late stage					
Attribute						
advantage						
3	Finishes Solutions					
Criteria	Various solutions are available					
Attribute						
advantage						
4	Design Process					
Criteria	The easier process the better					
Attribute						
advantage						
5	Design Connections					
Criteria	Easy Connections are better					
Attribute						
advantage						
6	Ability to Modify at On-site					
Criteria	Open for future iteration					
Attribute						
advantage						
7	Thermal Protection Solutions					
Criteria	Further treatment is not better					
Attribute						
advantage						
8	Fire Resistance					
Criteria	Account for fire is better					

Attribute						
advantage						
9	Earthquake Resistance					
Criteria	Account for earthquake is better					
Attribute						
advantage						
Quality						
1	Quality Control					
Criteria	The higher the level of control is better					
Attribute						
advantage						
2	Customer Satisfaction					
Criteria	A good satisfaction level is needed					
Attribute						
advantage						
3	Overall Quality: Robustness					
Criteria	The more robust the better					
Attribute						
advantage						
4	Durability					
Criteria	The more durable the better					
Attribute						
advantage						
5	Building Aesthetics					
Criteria	A great appearance is needed					
Attribute						
advantage						
Health and Safety (On-Site Risk Reduction)						
1	Workplace Accidents					
Criteria	Avoid accidents are better					
Attribute						
advantage						
2	Safety Requirement					
Criteria	Less safety requirement is better					
Attribute						
advantage						
Sustainability						
1	Energy Consumption					
Criteria	Energy saving is desirable					
Attribute						
advantage						
2	On-site Waste					
Criteria	Minimize waste is desirable					
Attribute						
advantage						
3	Environment Impact					
Criteria	Less solid waste generation is desirable					
Attribute						
advantage						
4	LEED Certification					
Criteria	Achieve required certification					
Attribute						
advantage						

5	Reuse of Components					
Criteria	Recycling is desirable					
Attribute						
advantage						
6	Water Consumption					
Criteria	Water saving is desirable					
Attribute						
advantage						
Cost						
1	Design Cost					
Criteria	Minimal cost is preferable					
Attribute						
advantage						
2	Off-Site Components Cost					
Criteria	Minimal cost is preferable					
Attribute						
advantage						
3	On-site Labor Cost					
Criteria	Minimal level of labor is preferable					
Attribute						
advantage						
4	Heating and Cooling Energy Cost					
Criteria	Minimal cost is preferable					
Attribute						
advantage						
5	Maintenance Cost					
Criteria	Less cost is better					
Attribute						
advantage						
6	Additional Cost (Correct Design and Manufacturing Errors)					
Criteria	Minimal cost is preferable					
Attribute						
advantage						
Time						
1	Design Time					
Criteria	Short duration is advisable					
Attribute						
advantage						
2	Installation and Assembly Time (On-site Work)					
Criteria	The faster the better					
Attribute						
advantage						
3	Coordinate Time					
Criteria	The faster the better					
Attribute						
advantage						
4	Overall Construction Time					
Criteria	The faster the better					
Attribute						
advantage						
Process						

1	Logistics					
Criteria	Rapid logistics is needed					
Attribute						
advantage						
2	Possibility of Damage During Transport					
Criteria	Minimal damage should be achieved					
Attribute						
advantage						
Sum						

34 factors and 34 criteria were considered in the evaluation process. To complete this table, the participants inserted the attributes of each off-site option. Then, they selected the least preferred off-site attribute for each factor, and compared it with the advantage of each other alternative's attribute. Next, they scored their opinion on the other advantages proportionally and estimated the importance of advantages for each factor. Finally, the suitable off-site components with the highest combined score was chosen.

CHAPTER 7

ANALYSIS AND DISCUSSION OF RESULTS

7.1 Analysis and discussion of the AHP survey results

The first part of the third section in the AHP survey has investigated the type of off-site systems that are used in each company and the reasons behind this adoption. It was found that off-site companies have chosen the systems according to personal experience without using any rigorous data. Additionally, it was established that the construction participants have agreed that adopting a decision support tool to choose the optimal off-site systems can potentially shrink the disadvantages while expanding the advantages of this method. The next part of the third section asked the participants to fill the pairwise comparison with respect to a set of criteria (cost, time, quality, health & safety, sustainability and process).

A total of 24 construction companies (14 in Lebanon and 10 in Syria) responded out of 35 surveys sent, whereby most of them have more than 5 years of experience in this field. The data gathered from the construction managers consists of pair-wise comparisons for multiple criteria. Next, further analysis was conducted to combine the individual comparison judgements from participants so that a single comparison matrix for each Lebanese and Syria participant is produced. This was achieved by computing a geometric average for each response and checking for its consistency. Afterwards, proper mathematical procedures were implemented to compute the importance of each criterion relative to the goal and calculate a weight for each off-site option/alternative. Table 9 presents the results of pairwise comparisons of one criterion with respect to the other criteria for Lebanese participants. Results reveal that the health and safety, quality, sustainability and process criteria ranked higher than cost. However, the cost ranked higher than time. These results reveal the importance of other criteria in the decision making process that are often understated. Hence, criteria other than cost and time should be considered when adopting off-site methods.

Table 9 - The pairwise comparison of one criterion with respect to the other criteria for Lebanese survey participants

Criteria	Cost	Time	Quality	Health and Safety	Sustainability	Process
Cost	1	1.530	0.467	0.223	0.346	0.813
Time	0.656	1	0.253	0.172	0.275	0.357
Quality	2.0765	3.739	1	0.625	1.251	1.654
Health and Safety	4.338	5.639	1.426	1	1.795	2.596
Sustainability	2.799	3.641	0.695	0.557	1	1.588
Process	1.229	2.799	0.498	0.385	0.629	1

Figure 24 demonstrates that the health and safety criterion has the highest weight against time (5.6), followed by cost, process, sustainability and quality with (4.3), (2.6), (1.8) and (1.4) respectively. Also, the health and safety has the highest importance when compared with cost (4.3), followed by sustainability, quality, process and time with (2.8), (2.1), (1.2) and (0.7), respectively.

Figure 24 - The pairwise comparison of one criterion with respect to the other criteria for Lebanese survey participants

On the other hand, Table 10 presents the results of the pairwise comparisons of one individual criterion with respect to the other criteria for Syrian participants. Results also reveal that the health and safety, quality, and sustainability criteria graded high when compared to the cost factor. However, the cost criterion was ranked as more important than the time and process factors. The difference in the priority of one criterion over the others between construction participants in Lebanon and Syria, can be explained by one of the reasons that the roads in Syria are less crowded than in Lebanon which improves the process factors: project access, logistics and the installation of off-site units.

Table 10 - The pairwise comparison of one individual criterion with respect to the other criteria for Syrian survey participants

Criteria	Cost	Time	Quality	Health and Safety	Sustainability	Process
Cost	1	2.509	0.343	0.265	0.441	1.549
Time	0.397	1	0.224	0.173	0.234	0.682
Quality	2.913	4.047	1	0.761	0.913	2.545
Health and Safety	3.766	5.460	1.072	1	1.436	4.681
Sustainability	2.268	4.281	0.857	0.695	1	3.185
Process	0.645	1.462	0.279	0.214	0.383	1

Figure 25 illustrates that the health and safety criterion has the highest weight against time (5.5), followed by process, cost, sustainability and quality with (4.7), (3.8), (1.4) and (1.1) respectively. Another important observation in Figure 25 is that the health and safety factor has also the highest importance when compared with cost (3.8), followed by quality, sustainability, process and time with (2.9), (2.3), (0.6) and (0.4), respectively.

Figure 25 - The pairwise comparison of one criterion with respect to the other criteria for Syrian survey participants

Table 11 and Figure 26 comparatively assess the results considering the cost criterion. It can be noticed that the Lebanese participants prefer the panelized systems over others when the decision is based on cost. The use of the panel method to fabricate off-site units might produce the least costly system, while the hybrid and natural material systems were the most expensive.

Table 11 - The pairwise comparison matrix with respect to the cost criterion for Lebanese survey participants

Alternatives	Panelized System	Natural System	Volumetric System	Hybrid System
Panelized System	1	2.747	1.329	1.845
Natural System	0.364	1	0.757	0.993
Volumetric System	0.752	1.369	1	2.132
Hybrid System	0.542	0.970	0.469	1

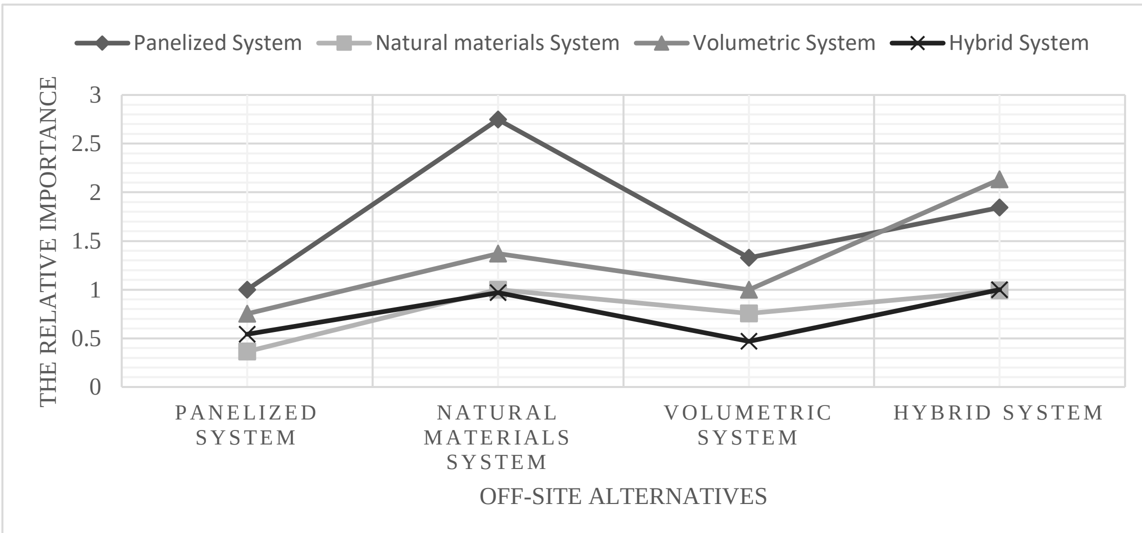

Figure 26 - The pairwise comparison results with respect to the cost criterion for Lebanese survey participants

According to Table 12 and Figure 27, if only "cost" is considered when making off-site decisions, the panelized system would be the most suitable in Syria, followed by hybrid, natural materials, and volumetric systems. The volumetric system has a minimum weight (0.47) compared to the panelized system, followed by hybrid (0.55) and natural materials systems (0.80). This emphasizes that the volumetric system requires a higher initial investment and is considered the most expensive off-site solution. This system is the most efficient only when used for large quantity of identical units.

Table 12 - The pairwise comparison matrix with respect to the cost criterion for Syrian survey participants

Alternatives	Panelized System	Natural System	Volumetric System	Hybrid System
Panelized System	1	3.232	1.805	1.404
Natural System	0.309	1	1.257	0.912
Volumetric System	0.467	0.796	1	0.549
Hybrid System	0.673	1.095	1.817	1

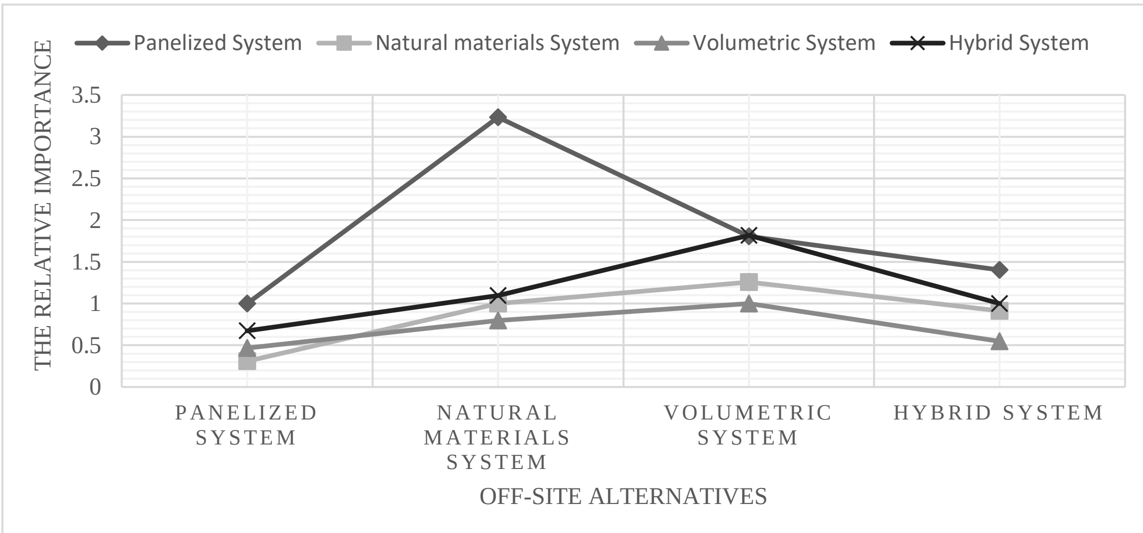

Figure 27 - The pairwise comparison results with respect to the cost criterion for Syrian survey participants

Other pairwise comparison results for both sets of participants were made and analyzed with respect to the time, quality, health and safety, sustainability and process criteria.

Another analysis was conducted to calculate the weighted average for each decision alternative. This rating helps in selecting the suitable off-site system based on the Lebanese participant's objective. Table 13 and Figure 28 depict respective results. The health and safety factor affects mostly in making a decision (33.4%) followed by quality, sustainability, process, cost and time with (20.9%), (19.4%), (12.3%), (8.5%) and (5.4%), respectively.

Table 13 - The weighted average rating for each decision alternative for Lebanese survey participants

Criteria	Cost	Time	Quality	Health and Safety	Sustainability	Process	Weighted Average Rating
Alternatives	0.085	0.054	0.209	0.334	0.194	0.123	
Panelized System	0.379	0.285	0.175	0.188	0.253	0.241	**22.56 %**
Natural System	0.169	0.060	0.108	0.213	0.218	0.066	**16.20 %**
Volumetric System	0.286	0.355	0.384	0.333	0.266	0.339	**32.86 %**
Hybrid System	0.166	0.299	0.333	0.266	0.264	0.354	**28.38 %**
Sum	1	1	1	1	1	1	**100 %**

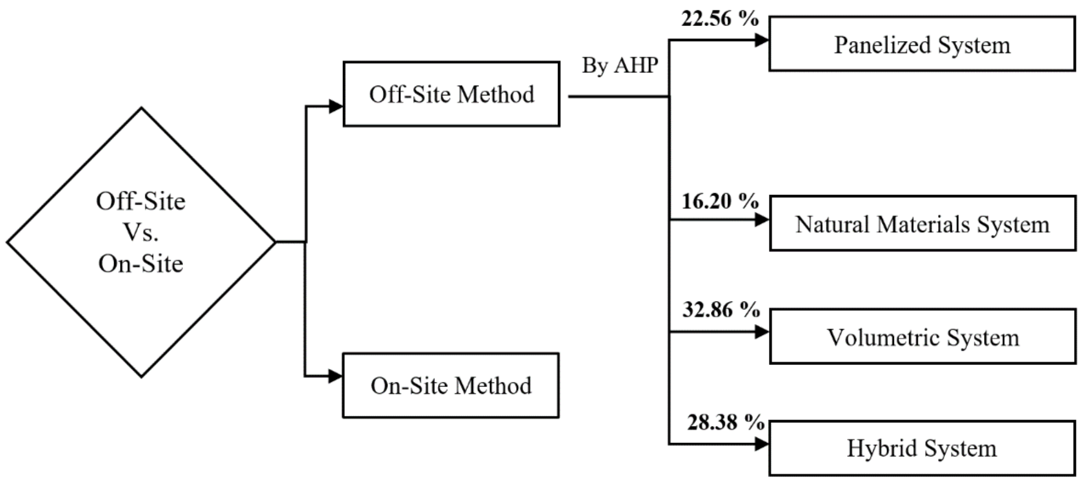

Figure 28 - The decision tree for selecting from the four off-site systems for Lebanese survey participants

Results reveal that participants in Lebanon prefer to opt for the volumetric systems (rating about 32.86%) as opposed to other systems such as natural materials systems (16.20%), panelized systems (22.56%), or hybrid systems (28.36%).

Also, another analysis was done to compute the weights for each off-site decision alternative. This rating helps in selecting the suitable off-site system based on the Syrian participant's objective. Table 14 and Figure 29 depict respective results. The health and safety has achieved the highest effect on making a decision (31.9%) followed by quality, sustainability, cost, process and time with (22.9%), (22.5%), (10.2%), (7.3%) and (5.1%), respectively. The results from both sets of participants show that the health and safety factor is the highest criterion with respect to others.

Table 14 - The weighted average rating for each decision alternative for Syrian survey participants

Criteria	Cost	Time	Quality	Health and Safety	Sustainability	Process	Weighted Average Rating
Alternatives	0.102	0.051	0.229	0.319	0.225	0.073	
Panelized System	0.402	0.130	0.114	0.151	0.099	0.253	**16.28 %**
Natural System	0.183	0.066	0.095	0.250	0.329	0.222	**21.41 %**
Volumetric System	0.160	0.410	0.459	0.314	0.309	0.267	**33.19 %**
Hybrid System	0.255	0.393	0.333	0.285	0.262	0.257	**29.12 %**
Sum	1	1	1	1	1	1	**100 %**

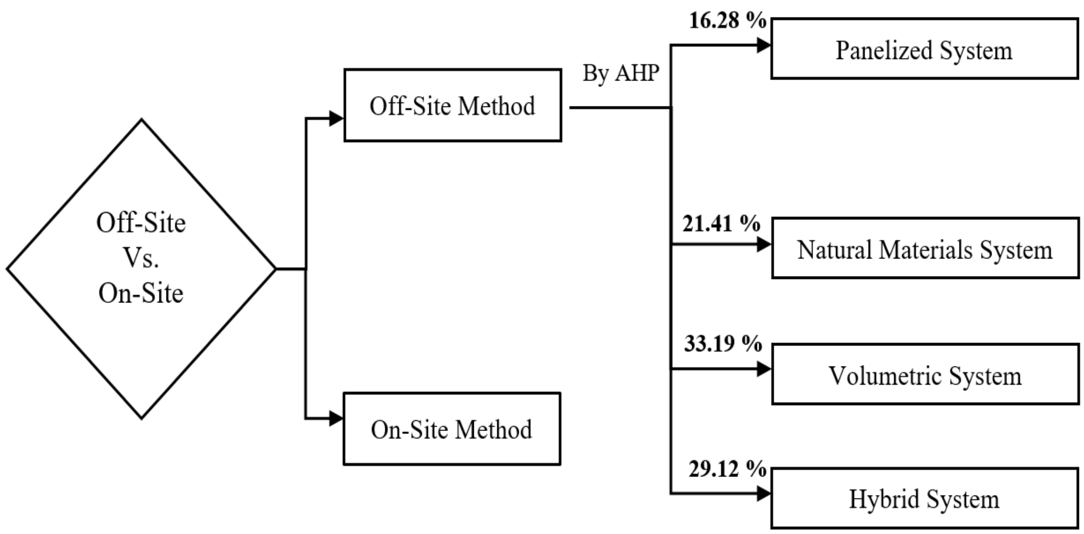

Figure 29 - The decision tree for selecting from the four off-site systems for Syrian survey participants

On the other hand, as shown in Figure 29, Syrian participants preferred to choose the volumetric systems (with a weighted average rating around 33.19 %). The other weighted scores in the AHP analysis were about 16.28 % for the panelized alternative, followed by 21.41% for the natural materials and 29.12% for the hybrid option.

Both sets of participants agree that the volumetric option is the most suitable, because they believe this option can rapidly be executed. However, they disagree in the least suitable option. The Lebanese participants do not prefer the natural material system whereas the Syrian participants prefer it over the panelized system. This can be attributed to the fact that Syria is a large country with more natural resources than Lebanon.

To sum up, these results can aid practitioners in identifying and selecting the optimal off-site methods given a certain project and based upon various factors (e.g. cost, time, waste, quality, health, safety etc.). The AHP survey results show the advantages of each off-site system with respect to the factors tested. Moreover, the AHP results show the need for optimally selecting off-site methods to drive more value into the construction process.

7.2 Analysis and discussion of the CBA results

A total of 24 off-site construction stakeholders participated in the CBA analysis: AUB’s engineering students (majoring in architecture and graphic design) constitute around (33.33%) of the participants, while the remaining (66.67%) varied among off-site contractors (33.33%), AUB’s professors at the department of architecture and design (16.67%) and the facility planning and design unit members at the American University of Beirut (16.67%). Most of participants emphasized the importance of the established factors (Table 10) on the final decision. The importance of advantages of the established factors and the accumulated scores for each off-site option are calculated and presented below, based on the data filled in the CBA table. The purpose of these results is to illustrate the effect of each factor in choosing the suitable off-site component and to highlight the difference in making a decision when it comes to different construction stakeholders (i.e. users, professors, owners and contractors).

7.2.1 Owners feedback

As displayed in Figure 30, results of the CBA case study show that owners would rather opt for the sandwich steel panels with an accumulated score of 1898 upon grouping all factors (i.e. Design and Execution, Quality, Health and Safety, Sustainability, Cost, Time and Process). Nevertheless, this option scores the lowest rate with respect to the quality, and health & safety factors. However, if the decision is taken based only on design & execution, quality and health & safety factors, the owners would select the precast concrete panels. On the other side, other factors such as sustainability, cost and time ranked the lowest for the case of precast concrete panels.

From the owners' perspective, details of the scores for each factor are displayed in Figure 31. In summary:

- Precast concrete panels and composite solid precast sandwich panels gain the highest score on durability with 92.5% and 90%, respectively. However, both options record the lowest average on safety requirements with 5% and 10%, respectively as heavy members are used and thereby require more safety procedures for assembly and installation.
- Light-weight steel open panels score the highest on ability to be modified on-site with 87.5%. While this option ranks the lowest on safety requirements with 20%, due to the

fact that open panels need a more work on-site and therefore more on-site safety considerations.

- Light-weight steel closed panels gain the highest score on water consumption with 85% whilst they record the lowest score on robustness with 17.5%.
- Finally, the design flexibility of sandwich steel panels (with a score of 95%) records the highest in terms of advantages. This result emphasizes that sandwich steel panels can be modified even at a later stage. However, they gain the lowest score with 5% on both fire and earthquake resistance, which reveals that owners don’t believe that these panels can resist fire and earthquake hazards.

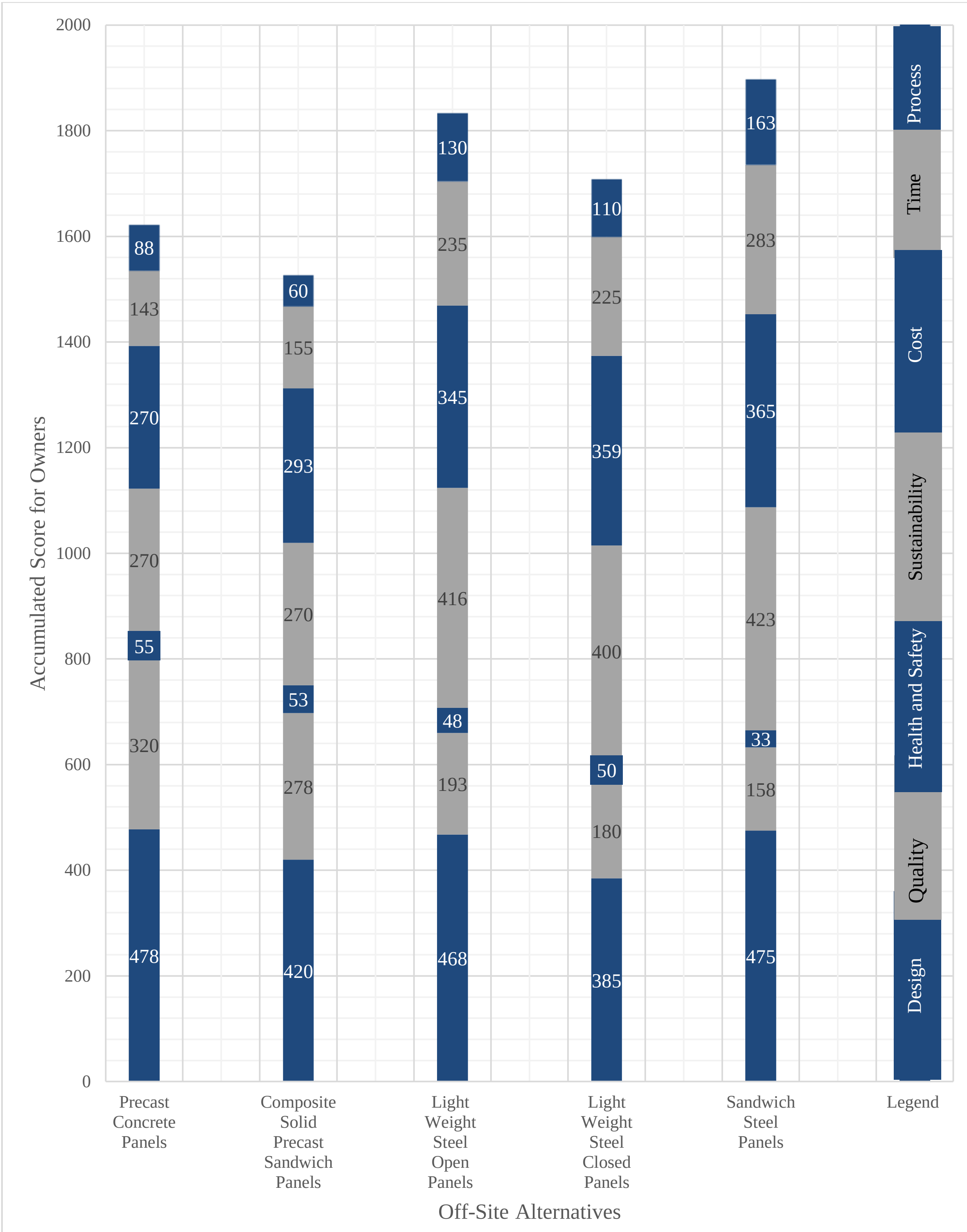

Figure 30 - The accumulated score for owners

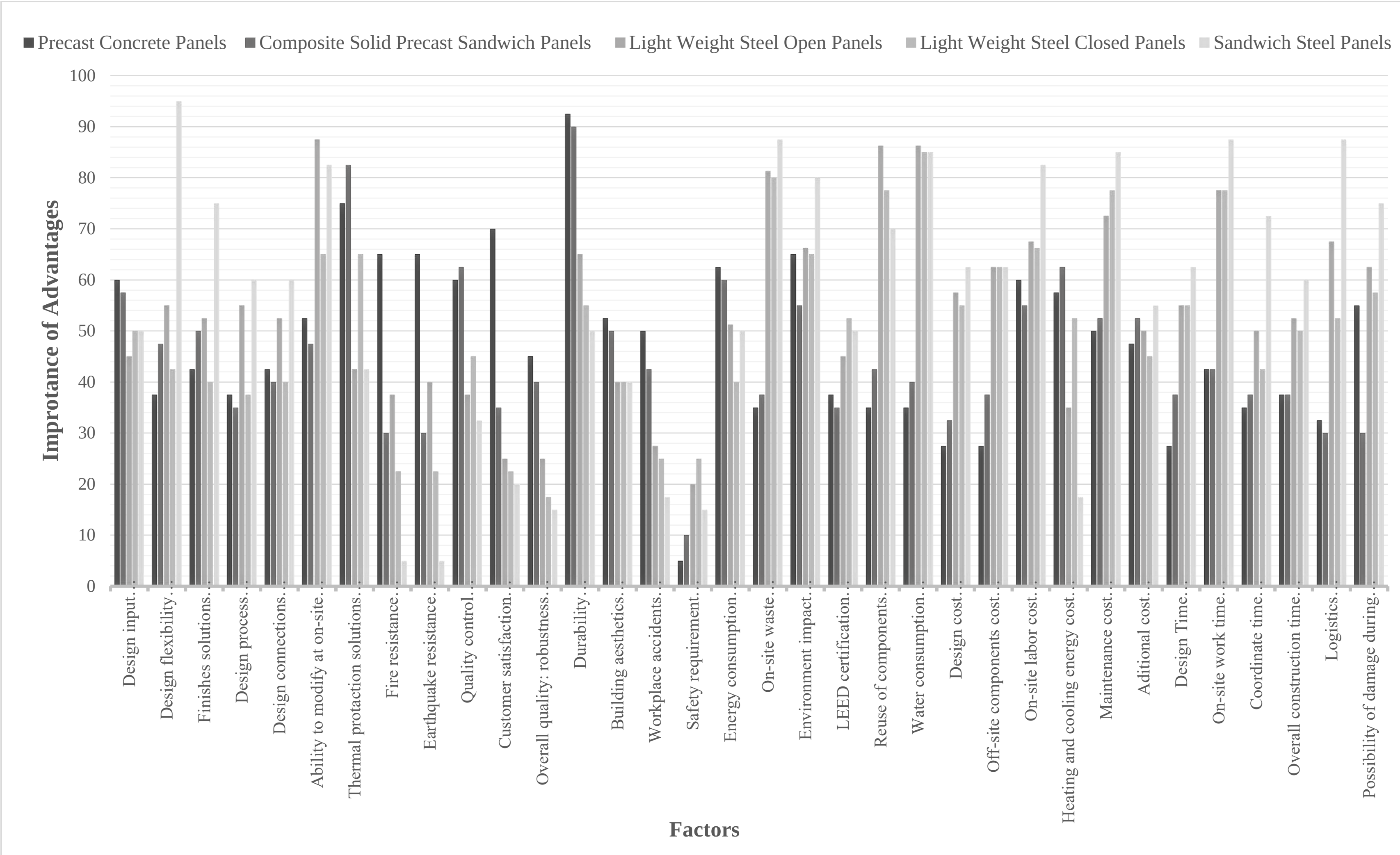

Figure 31 - The importance of advantages for the group of factors (Owners Feedback)

7.2.4 Contractors feedback

As shown in Figure 32, results of the CBA case study show that off-site contractors in Lebanon and Syria adopt the sandwich steel panels the most with an accumulated score of 2165 upon grouping all factors and give the highest score to design & execution, cost and time factors. Nevertheless, this option records the lowest on quality and health & safety factors. However, if the decision is based on the quality, sustainability, and health & safety, the contractors would rather opt for the lightweight steel closed panels. The choice would also be the lightweight steel closed panels when design & execution and cost factors are taken into consideration.

Based on the contractors' perspective, details of the scores for each factor are displayed in Figure 33. In summary:

- Precast concrete panels get the highest score on finishes solution with 81.3%, and rank the lowest on energy consumption with 20.6 %.
- Composite solid precast sandwich panels gain the highest score on thermal protection solutions with 76.3% and record the lowest on energy consumption with 25 %. This option, like the precast panels, is the least adopted when energy savings are considered.
- Light-weight open panels achieve the highest score on logistics and reuse of components with 87.5 %. However, they rank the lowest on energy consumption with 25 %.
- Light-weight closed panels gain the biggest highest score on water consumption with 83.8 % and record the lowest on additional cost (design and manufacturing errors) with 28.1 %.

- Sandwich steel panels record the highest score with 87.5 % with respect to water consumption, design cost, design time and coordinate time factors. However, this option gets the lowest average on both customer satisfaction and safety requirements factors (18.1%).

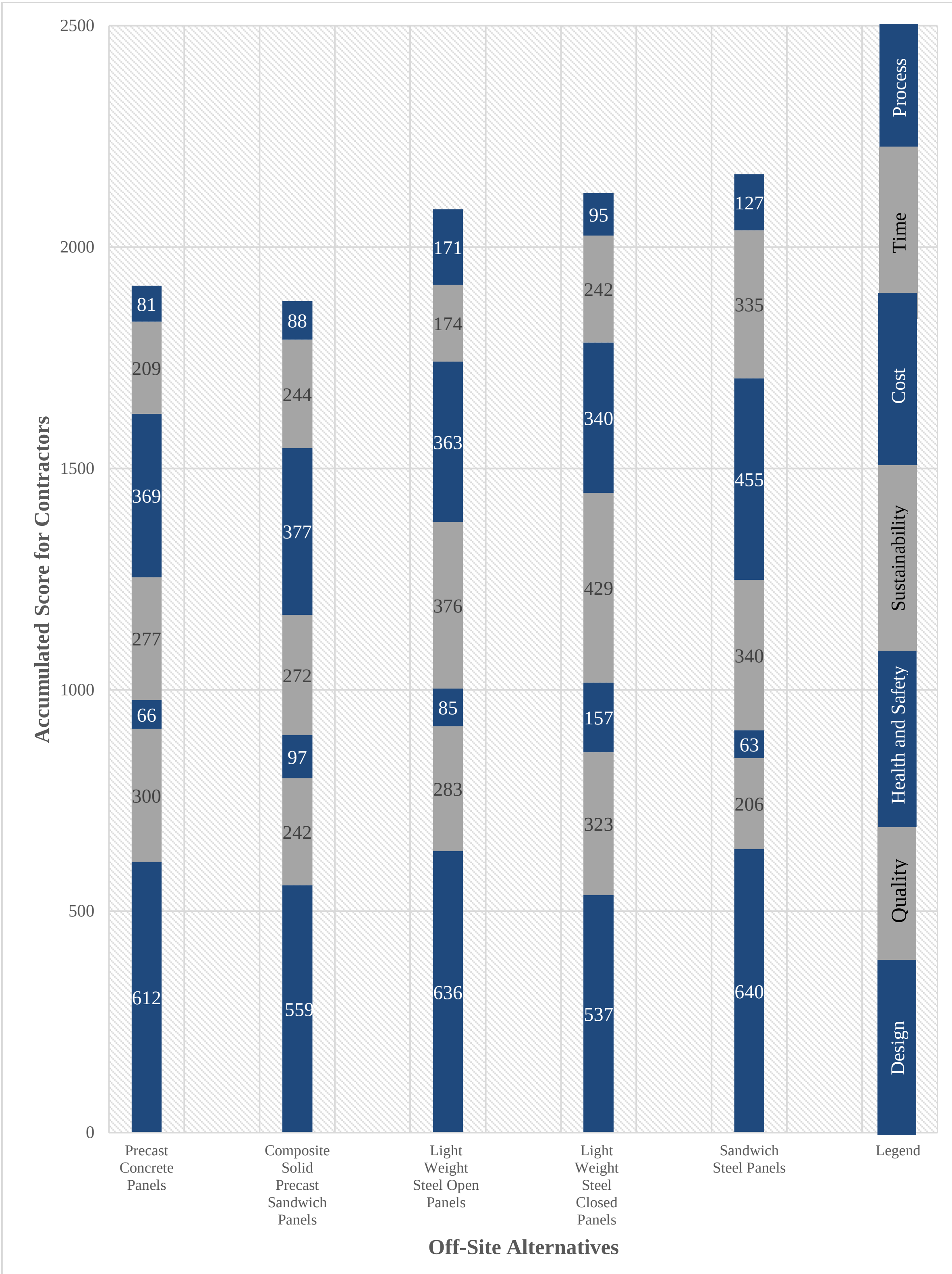

Figure 32 - The accumulated score for contractors

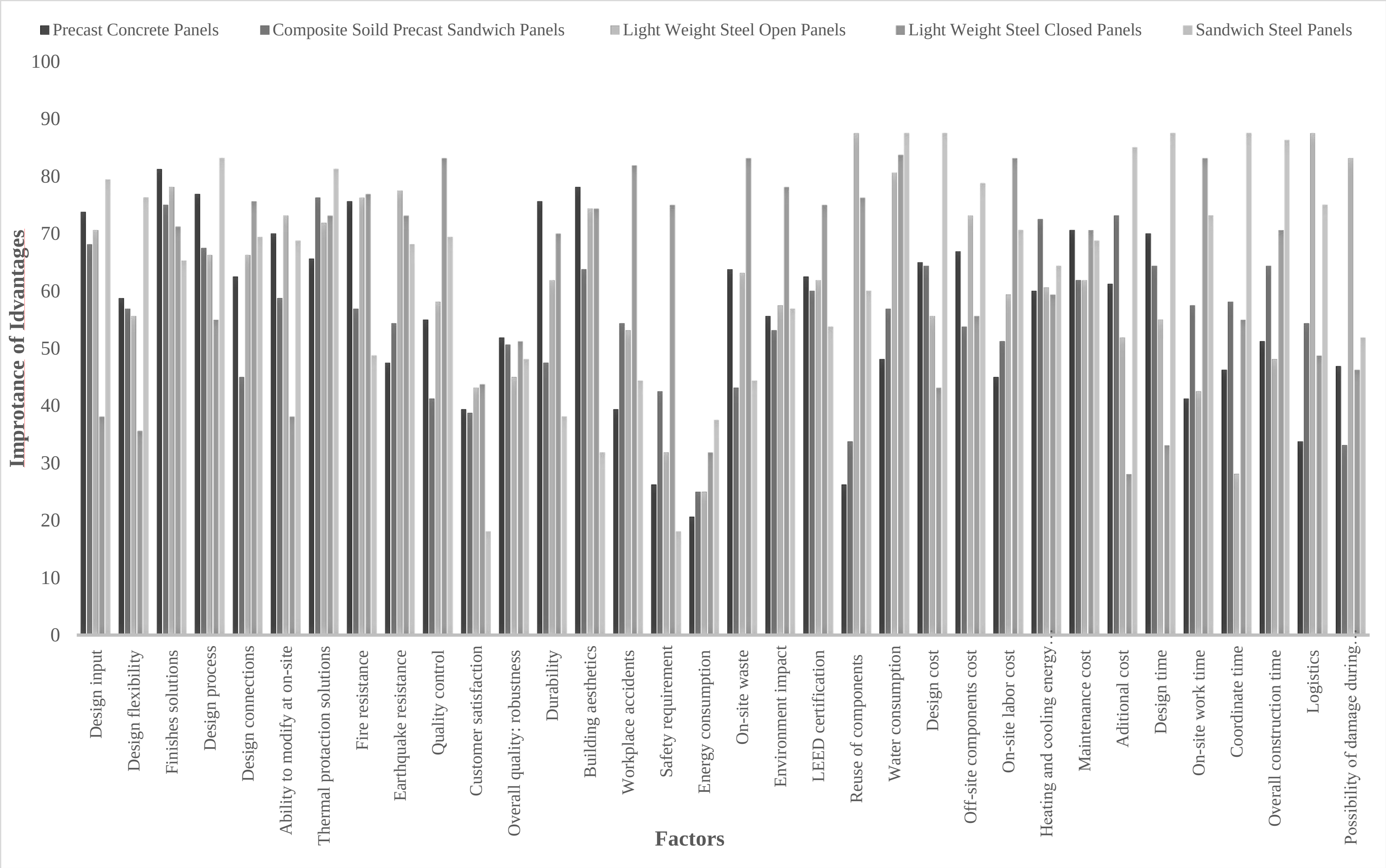

Figure 33 - The importance of advantages for the group of factors (Contractors Feedback)

7.2.3 Professors feedback

As presented in Figure 34, results of the CBA case study highlight that professors mostly prefer the precast concrete panels with an accumulated score of 2198 upon grouping all factors and accord the highest score to these panels with respect to the quality and cost factors and the lowest with respect to time. However, they opt for the composite solid precast sandwich panels when the decision targets mostly the sustainability, cost, and time factors. The decision switches to the light weight closed panels when the health& safety and process factors are taken into consideration. Moreover, the professors give the sandwich steel panels the lowest rate for design& execution, sustainability, cost, and quality factors.

Details of the scores for each factor are displayed in Figure 35 from the faculty members' perspective. In summary:

- Precast concrete panels record the highest score with respect to the following group of factors: design connections, building aesthetics, fire resistance, on-site waste and environment impact with 95% and rank the lowest on design process with 12.5 %. This is because precast concrete panels are more difficult to design than others.
- Composite solid precast sandwich panels record the highest average (with a score of 85 with respect to the following group of factors: energy consumption, environment impact, on-site waste, building aesthetics, durability, customer satisfaction, quality control, fire resistance, thermal protection solutions and design connections. However, these panels rank the lowest on maintenance cost and design input with 15 %.
- Light-weight open panels obtain the highest score on ability to be modified on-site with 95%. The open panels are delivered to the site without previously manufacturing any of

the windows, doors, services, internal wall finishes and external cladding and accordingly, they can be easily altered on site at a later stage. However, they record the lowest score on design process with 17.5 %.

- Light-weight closed panels score 87.5% on earthquake resistance, which reveals that professors strongly believes in the efficiency of these panels to resist earthquake hazards. However, they get the lowest score on design process with 12.5 %.
- Finally, sandwich steel panels record the highest score with 95% with respect to the logistics, overall construction time and coordinate time factors. This is because professors perceive the sandwich steel panels as an easy and fast option. However, sandwich steel panels get the lowest score on the design process with 2.5 %.

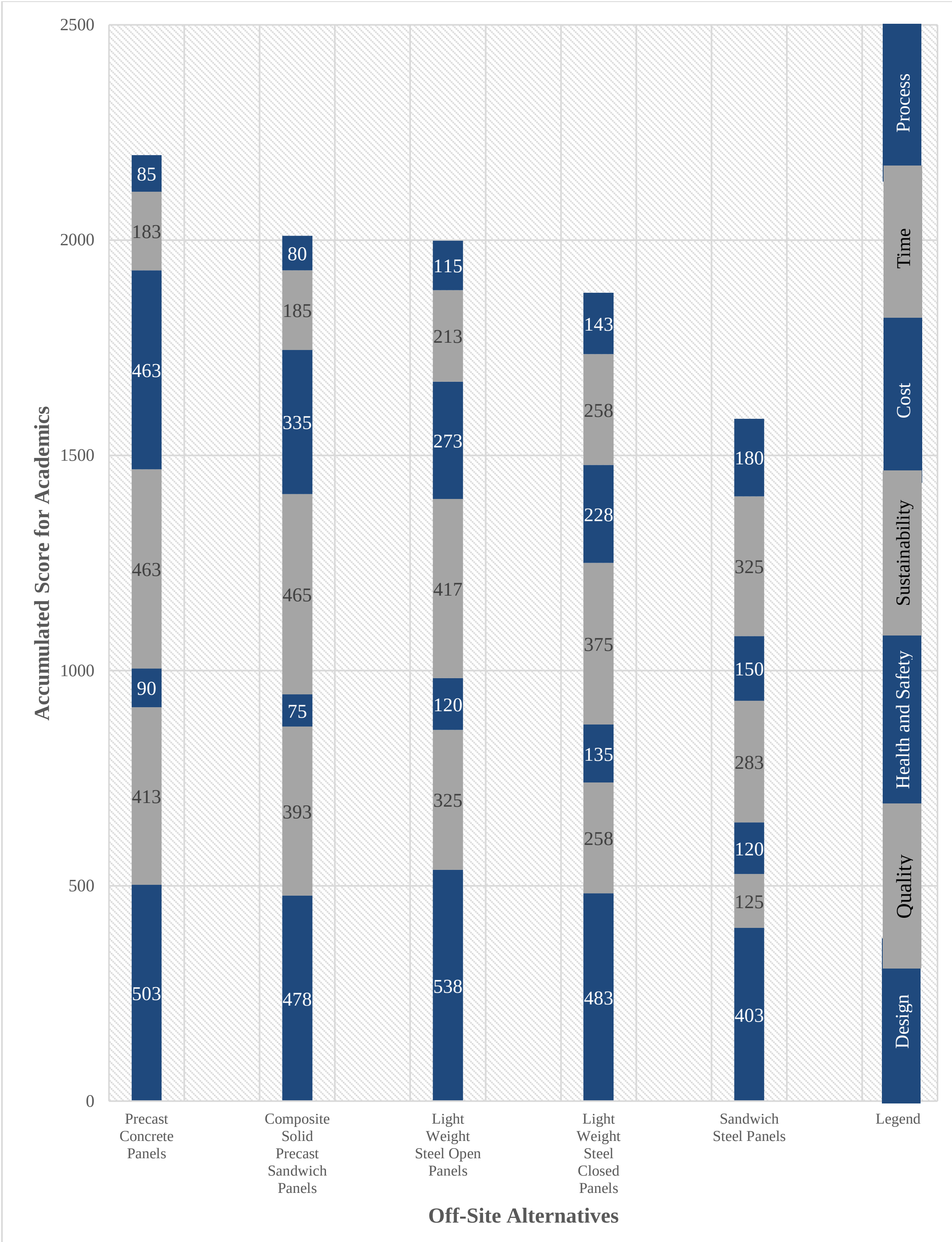

Figure 34 - The accumulated score for professors

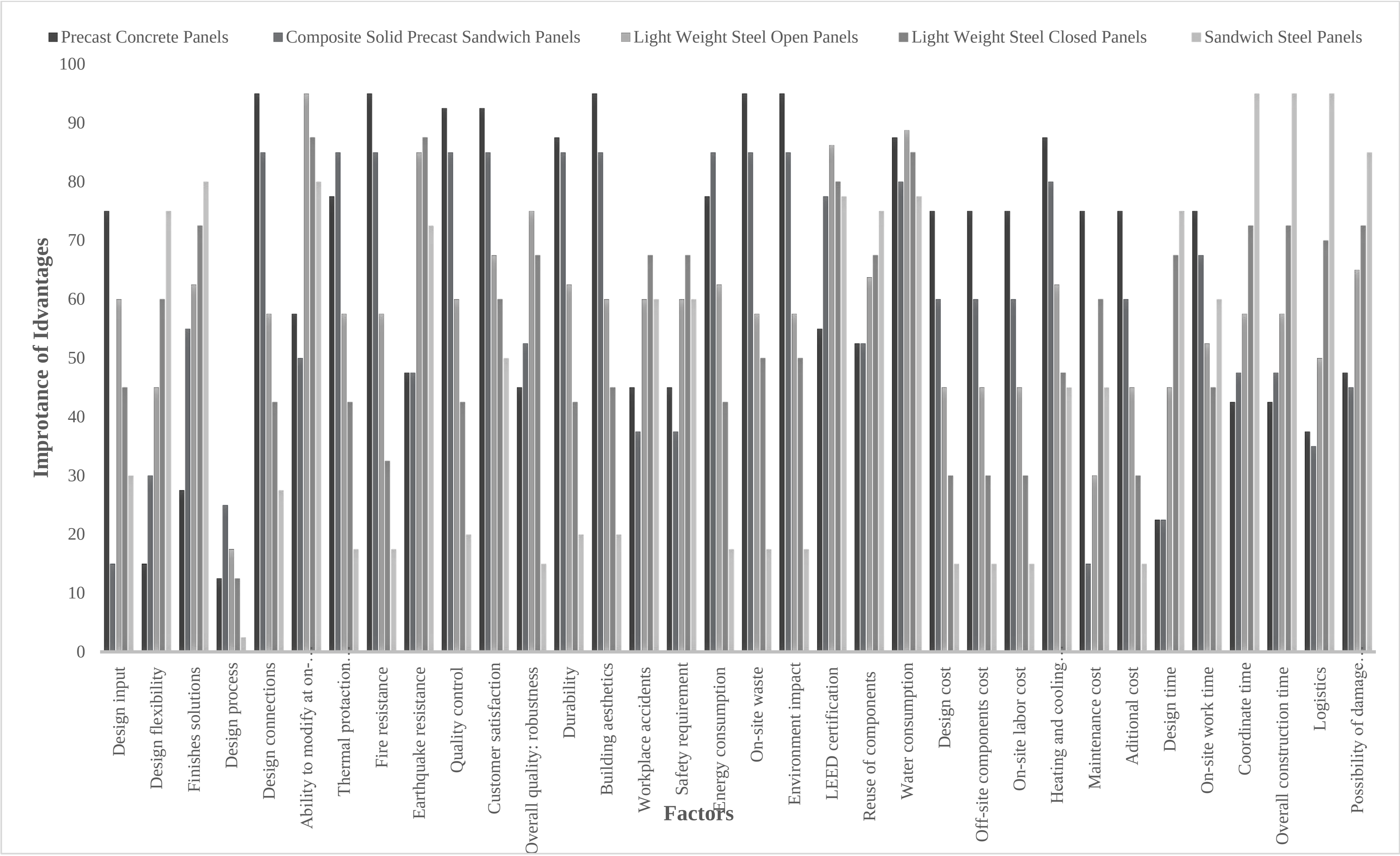

Figure 35 - The importance of advantages for the group of factors (Professors Feedback)

7.2.4 Users feedback

As presented in Figure 36, the outcomes of the CBA case study show that users preferred the precast concrete panels the most with an accumulated score of 1830 upon grouping all factors and accord the highest score on quality, cost and process factors. However, they would opt for the composite solid precast sandwich panels when the decision is based on design & execution, sustainability and cost. On the other side, the time factor records the lowest in the case of the composite solid precast sandwich panels. Also, health & safety, cost, and quality scored the lowest in the case of the light weight open steel panels, the light weight steel closed panels and the sandwich steel panels, respectively.

Details of the scores for each factor from the users' perspective are displayed in Figure 37. In summary:

- Precast concrete panels record the highest score on heating and cooling energy cost with 100% and the composite solid precast sandwich panels rank the highest on earthquake resistance with 95%. However, both options gain the lowest average on design flexibility with 1.9% and 7.5%, respectively. These scores reflect the perceived complexity by users in modifying the concrete panels at a later stage.
- Light-weight steel open panels obtain the highest score with 89.4% on reuse of components. This option scores, however, the lowest on robustness with 2.5%.
- Light-weight steel closed panels gain the highest score with 91.3 % on overall construction time. The closed panels include factory-manufactured windows, doors, services, internal wall finishes and external cladding and therefore need less time on-site to be assembled. However, they score the lowest on robustness with 11.3%.

- The design process of sandwich steel panels (with score of 100%) ranks the highest with respect to the importance of advantages. This score highlights the ease of designing sandwich steel panels. However, they get the lowest average on fire resistance with 5%, which reveals that users like owners don’t believe in these systems ability to resist fire hazards.
- Finally, the LEED certification doesn’t affect the decision making process based on users’ opinion.

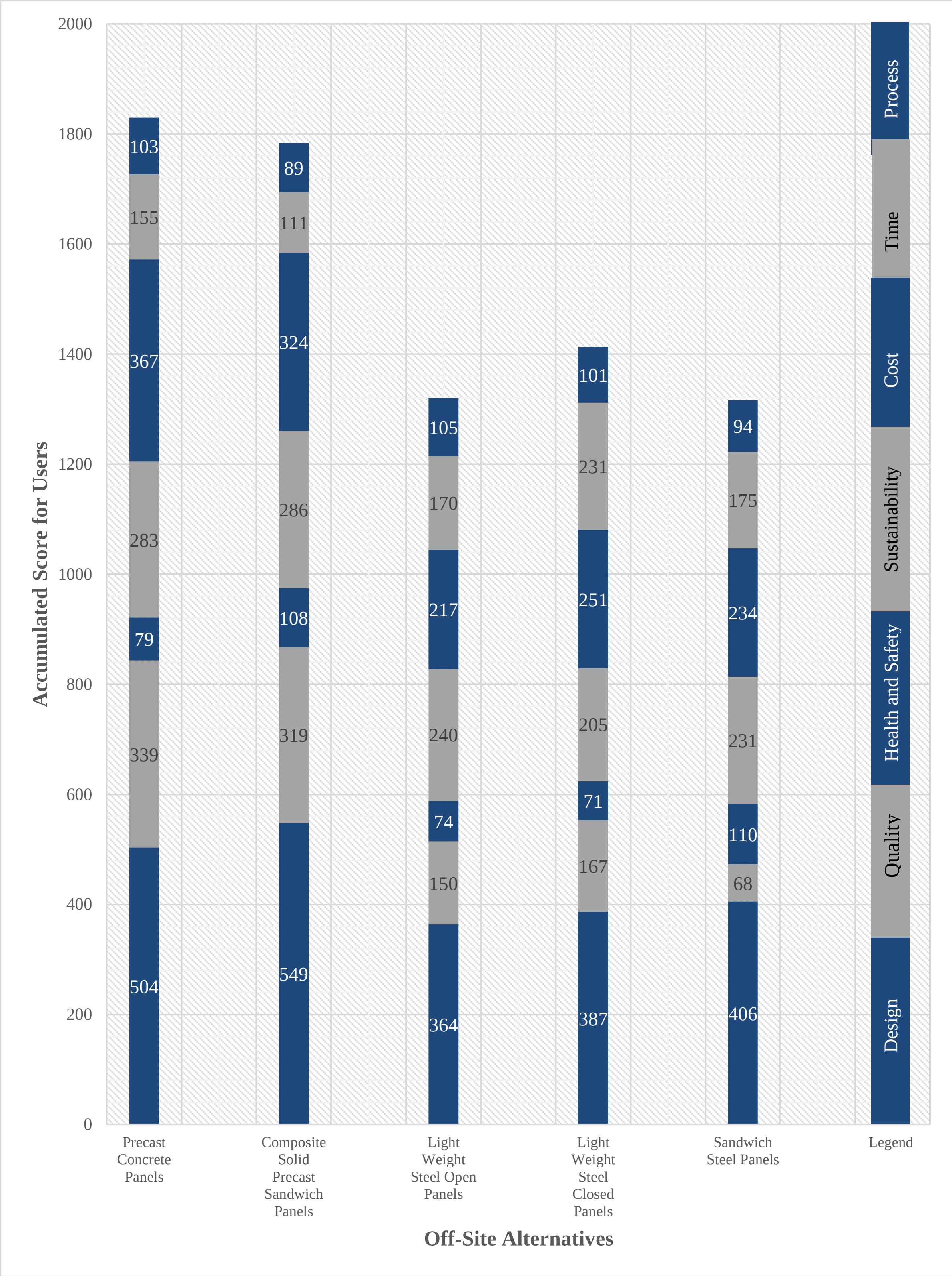

Figure 36 - The accumulated score for users

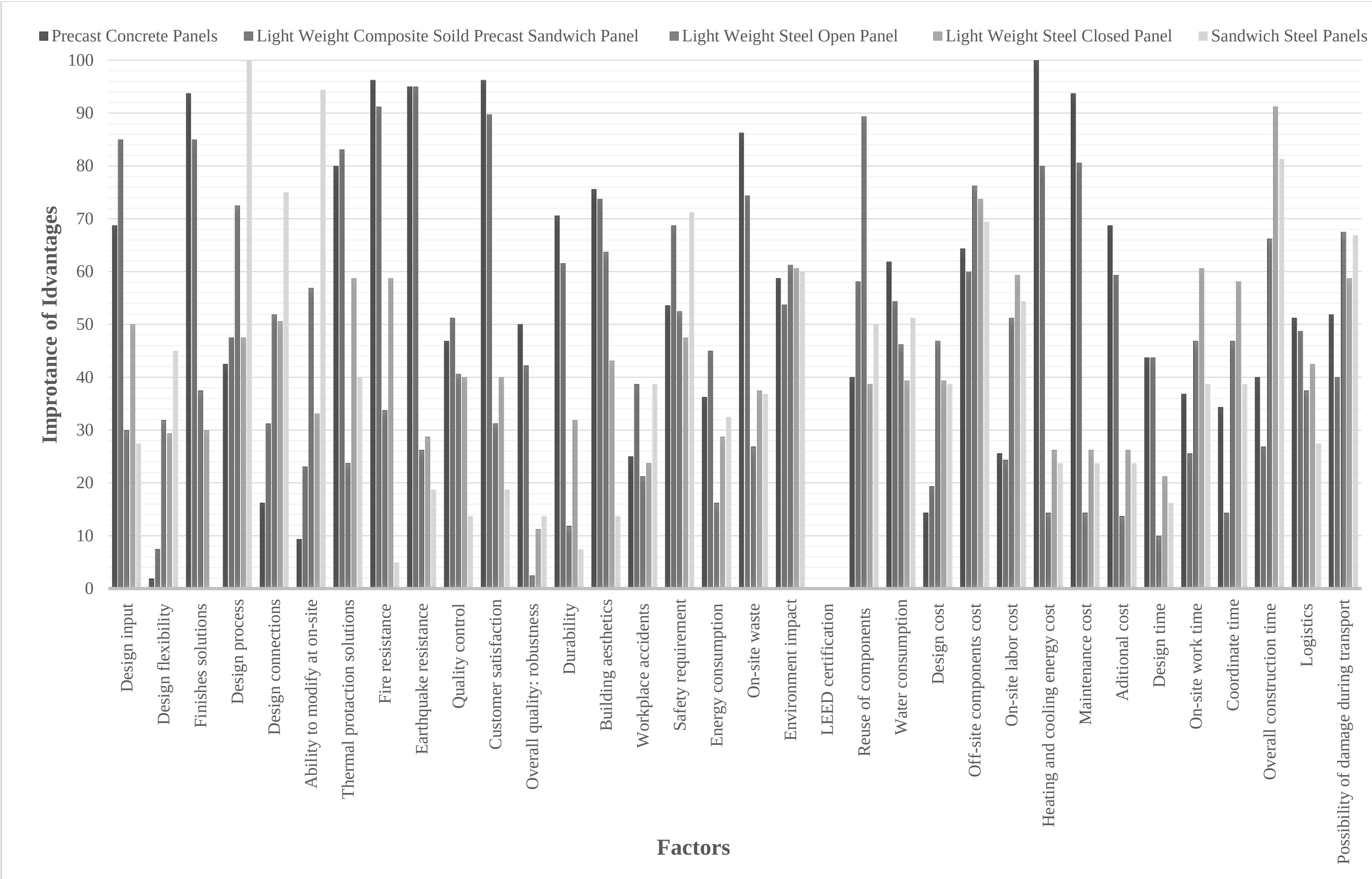

Figure 37 - The importance of advantages for the group of factors (Users Feedback)

7.2.5 Summary of the stakeholders' feedback

1. Owners and contractors opt to use the sandwich steel panels, while professors and users select the precast concrete panels as the most suitable option.
2. For the precast concrete panels:
    a. Owners, professors, and users assign the precast concrete panels the highest score with respect to the quality factor.
    b. Professors and users allocate the highest average with respect to the cost factor.
3. For the composite solid precast concrete sandwich panels:
    a. Professors and users rank the composite solid precast concrete sandwich panels as the highest option with respect to the sustainability factor.
    b. Professors and owners gave the composite solid precast concrete sandwich panels the highest on sustainability, cost, and time factors.
    c. Professors, owners, users, and contractors rank the composite solid precast concrete sandwich panels the lowest option with respect to the process factor.
4. For the lightweight open panels:
    a. Professors and users classify the open panels as the worst desirable choice on design & execution factors.
5. For the light-weight closed panels:
    a. Owners and contractors assign the closed panels as the least desirable choice on the design & execution factors.
    b. Professors, contractors, and users classify the closed panels as the lowest preferable option based on health & safety factors.

6. For the sandwich steel panels:
   a. Professors, owners, users, and contractors rank the sandwich panels as the highest option on time factors and as the lowest on quality factor.
   b. Owners, users, and contractors classify the sandwich panels as the highest option on cost factor.

7.2.6 Overall comparison across owners-contractors-professors-users

This section discusses (1) the difference in the highest scores given by all stakeholders to each off-site option with respect to the established factors as shown in Table 15 and (2) the variance in the importance of the off-site options among the different stakeholders as shown in Figure 38. Below is a comparative assessment based on Figure 38:

- Precast concrete panels and composite solid precast sandwich panels are given the highest importance of advantages by professors, which is not the case for owners.
- Light-weight steel open panels, light-weight steel closed panels and sandwich steel panels are scored the highest by contractors, which is not the case for users.

Table 15- Comparison of the highest scores given by all stakeholders to each off-site option with respect to the established factors

Stakeholders	**Off-Site Components**				
	Precast concrete panels	**Composite solid precast sandwich panels**	**Light-weight steel open panels**	**Light-weight steel closed panels**	**Sandwich steel panels**
Owners	Durability	Durability	Ability to be modified on-site	Water consumption	Design flexibility
Contractors	Finishes solution	Thermal protection solutions	Logistics and reuse of components	Water consumption	Water consumption, design time, design cost and coordinate time
Professors	Design connections, building aesthetics, fire resistance, on-site waste and environment impact	Energy consumption, environment impact, on-site waste, building aesthetics, durability, customer satisfaction, quality control, fire resistance, thermal protection solutions and design connections	Ability to be modified on-site	Earthquake resistance	Logistics, overall construction time and coordinate time
Users	Heating and cooling energy cost	Earthquake resistance	Reuse of components	Overall construction time	Design process

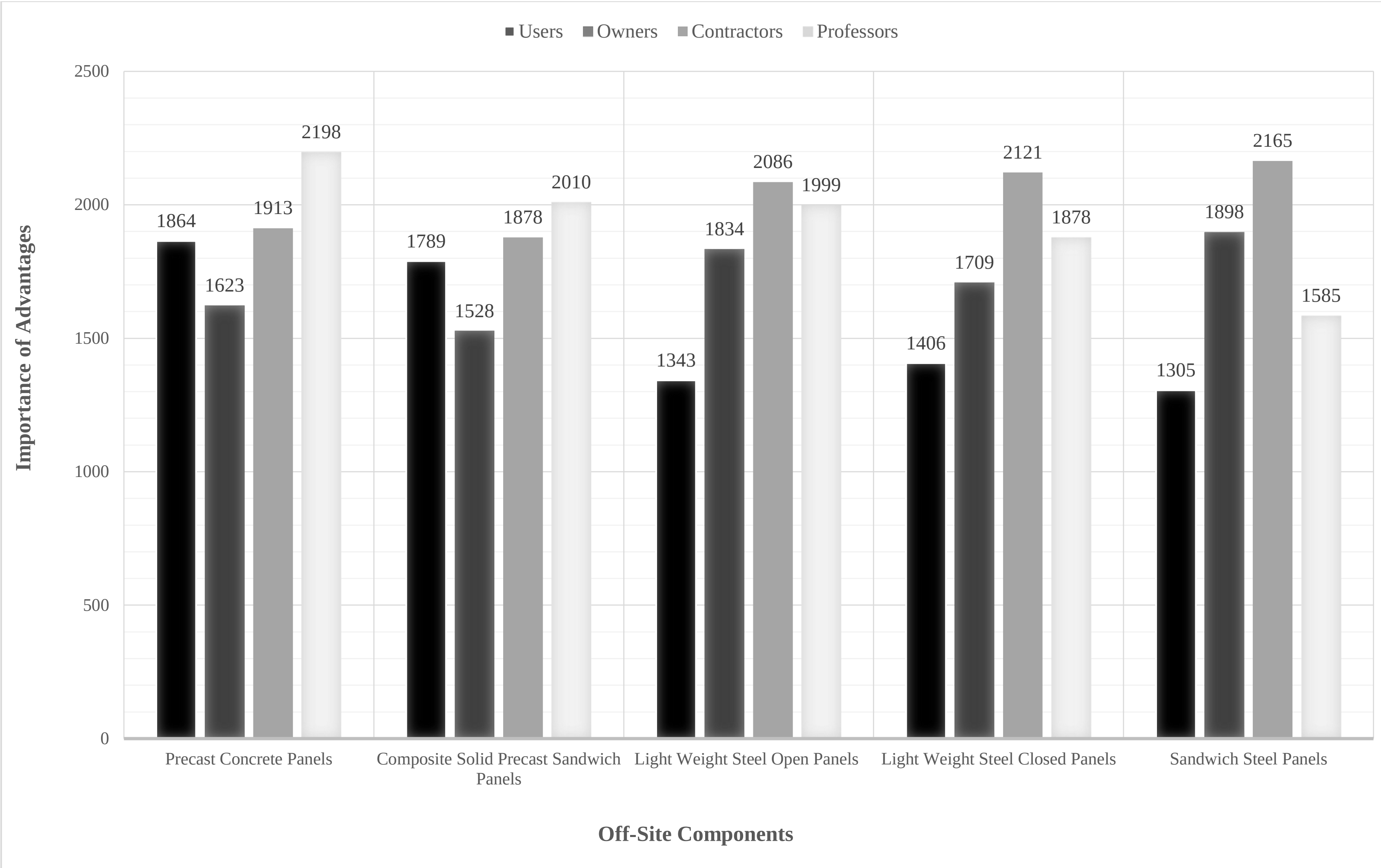

Figure 38 - Comparison of average scores given to each off-site option by all stakeholders

To sum up, these results demonstrate the conflict among stakeholders' result in the reduction in the level of user satisfaction. Therefore, to optimize the value of using off-site method, the decision should involve all stakeholders in selecting of the most suitable off-site option.

Because of the conflict in results when selecting the most suitable off-site option between construction stakeholders, two interviews were conducted, one with a senior project manager from FPDU at AUB (representing the owner), and another with the operation manager of the studio building representing the users.

To begin with, interviewees were asked about the process their decision makers followed to select sandwich steel panels for the studio building. Both agreed that the decision maker only considered the economic and rapid construction, and the ease of disassembly of the studio building after 2 to 10 years. The decision maker selected a steel temporary off-site building without taking into consideration neither the other available off-site options in Lebanon nor the other established factors in this study.

During the erection of the sandwich steel panels, several quality and safety deficiencies were found. The contractor came periodically to prevent the rainwater from penetrating inside the building. Besides, both of the interviewees noticed that the connections of the panels are bad. Finally, the assembly process of the sandwich panels didn't include any safety procedure. These deficiencies were witnessed because the decision maker focuses only on reducing the cost and time without considering the contractor's quality of work and health and safety factors.

Another important observation is that the decision maker did not give a significant time to design or even think of the educational design requirements. As a result, the sound insulation among the stories was very bad which affected the students in the studios. The owner resolved that by adding layers of acoustic isolators to reduce the noise and consequently paid an additional cost. Moreover, the interviewees stated that this decision delivered an educational building with poor thermal properties and consequently paid an extra cost for heating and cooling.

As seen above, the insights gathered from the interviews justify the dissatisfaction of users and professors towards adopting this option for the studio building. However, this decision would be more suitable for the users and professors if the decision maker had involved the architectural or graphic design department in the decision making process.

To sum up, these results prove the importance of using a decision support system while employing off-site methods. Applying choosing by advantages technique as a decision support system ensures quality, cost and time efficiencies. This technique compares among all available off-site options to maximize the value, especially that the decision maker's focus on cost and time did not generate a high level of value, neither did the lack of collaboration between stakeholders. The suggested decision support system could enhance the decision process, and improve the final product and overall satisfaction rates. In conclusion, this system splits the decision making process into smaller easy judgements and tackles each of them separately using different factors instead of focusing on the ill-determined problem.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Resorting to off-site construction is very important to continually improve current construction methods. However, none of the previous works have selected the optimal off-site systems and components for a given project while considering practitioners' value maximization. Furthermore, some literature research studies have attempted at comparing off-site construction against on-site construction but none have performed a comparison among panelized, natural materials, volumetric and hybrid systems. Moreover, no comparison was carried out among the components of each system. Therefore, there is a need to develop a decision making evaluation model that takes various stakeholders' goals into account to maximize the project value and highlights the difference among various off-site systems and components' attributes.

The aim of this research study is to design and develop a multi-criteria decision making tool for selecting the most appropriate off-site system and component to be adopted on construction projects in Lebanon and Syria while taking into account the clients' different goals (e.g., cost minimization, better safety records, etc.). Accordingly, the model is divided into two sequential levels whereby: (1) the analytical hierarchy process technique (AHP) is used in the first level for preliminary selection among panelized, natural materials, volumetric and hybrid systems, and (2) the choosing by advantages theory (CBA) is employed at the second level to consider the attributes of the chosen methods. The contribution of this research work lies in identifying the optimal off-site systems and components by creating a decision support system and in assessing and analyzing the attributes of the various off-site systems and components.

To achieve the research objectives, a study methodology is established to answer for the research questions at first. Following that, a literature review is conducted. It includes a search for past studies throughout several resources that relate to the off-site technology in construction. The study also concentrates on exploring the concept of off-site construction and analyzes the advantages and disadvantages of employing off-site method. The research helps in assessing whether it is appropriate to use the off-site method. Next, a thorough search in the Lebanese and Syrian manufacturing market is conducted to define the available off-site components, and to gather and categorize the information according to the main attributes such as cost, design, sustainability, time, waste, durability, safety, quality, environment, treatment and maintenance. Then, the combined key findings that were obtained from literature review and primary data are used to initially develop a conceptual model as a first stage of evaluation. The decision model is developed and tested for assigning weights to the four off-site categories (i.e. Panelized, Natural materials, Volumetric and Hybrid Systems) by the analytical hierarchy process. The analytical hierarchy process survey is conducted with selected senior managers from top off-site builders in Lebanon and Syria. Then, the alternative support system (i.e. the choosing by advantages) is used to assist in selecting an appropriate off-site component, based on the decision maker's objectives (e.g. cost minimization, better safety records, etc.). The choosing by advantages table is filled by a group of off-site stakeholders to compare among different options and estimate the importance of one option over others.

This research study offers various suggestions and recommendations which aimed at improving the application of the off-site method in construction projects. It takes the initial steps towards identifying the optimal off-site systems and components for a given project by extracting and elaborately analyzing the attributes of the off-site forms. The outcomes of this study consists of establishing standardized policies for properly choosing optimal off-site systems and components based on practitioners' goals. The recommendations of this research lie in providing various advised practices which can be applied by off-site stakeholders to maximize the value of employing this method. These recommendations are as follows:

- To increase value in future off-site projects, a shift in the decision making process is needed. Off-site practitioners are encouraged to invest in optimally selecting off-site systems to drive more value when adopting off-site method, and to shrink the disadvantages while expanding the advantages of off-site method. Also, they should enhance communication among project stakeholders during the decision making process to explore different attributes of off-site systems and components. Using the proposed decision support tool taking into account the various criteria will result in choosing the most convenient off-site system and component capabilities within a team of planners without considering their trades' requirements in a construction project, since it may not necessarily improve the emergent improvisational performance at the level of that project.
- To narrow down the conflicts among off-site stakeholders in future off-site projects and to deliver a better off-site project, an adjustment in making decision process is required. A decision should be involved all stakeholders to reduce cost and time, increase quality and safety, and deliver a sustainable off-site building. In addition, decision makers are encouraged to apply the proposed decision support tool in order

to explore the divergence in off-site stakeholders' opinions and improve the communication among different stakeholders. The proposed decision support tool leads to building up the global optimization and critical thinking in the decision making process, maximizing the value and eliminating the waste in utilizing the off-site method. Most importantly, applying the proposed decision support system helps the decision makers in focusing on those specific factors instead of concentrating on ill-defined problem.

Finally, limitations of this research study are worth stating to enhance future work. The scope of this study is limited to the off-site systems and components available in the developing countries such as Lebanon and Syria. The study can be applied only as a method to compare among off-site systems and components in the developed world. Potentially, this methodology could be applied to construction facilities like infrastructures; however, this would require further study. The study focuses on the following main off-site categorizes: panelized, natural materials, volumetric and hybrid systems. Other off-site categorizes such as: sub-assembly systems should be further studied. Moreover, the study analyzes the impact of the important factors on the decision making process. Other factors such as transporting and fitting the component to the site are not included. The research could be further developed to study the effect of other constraints on the decision making process. Finally, the off-site builders in Lebanon and Syria are limited. Therefore, conducting more interviews to fill the AHP survey and CBA case study would improve the outcomes of the decision support system.

APPENDIX

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