Configuration of Hybrid Modular Construction for Residential Buildings

Tarek Salama, Ahmad Salah, and Osama Moselhi

***Abstract*—Offsite and modular construction continue to gain momentum as an efficient approach for housing construction. Hybrid modular construction combines two or more offsite construction types (e.g. panelized) to minimize on-site construction activities. Researchers have presented case studies that overview the configuration system of hybrid construction however; these studies did not identify the constraints that affect sizes and dimensions of modules. This paper identifies the main factors affecting the configuration of modules in hybrid construction projects. The paper utilizes these factors to introduce a new configuration framework that is expected to assist hybrid construction stakeholders in identifying the most suitable configuration for each type of modules (i.e. panels) in their projects. A case study of a hybrid construction is selected to demonstrate the applicability of proposed framework and to highlight its capabilities in selecting the most suitable configuration of panelized projects. The results are discussed and conclusions are drawn to highlight the features of proposed framework.**

***Index Terms*—Configuration, hybrid construction, modular offsite construction.**

I. Introduction

Light gauge steel (LGS) off-site construction includes three main systems; volumetric or modular, panelized, and hybrid [1]. The ‘hybrid’ system combines modular and panel systems to optimize the use of 3D and 2D components in respect to space provision and manufacturing costs [2]. The light gauge steel (LGS) hybrid system is a cost-effective building solution for mid-rise residential buildings since it provides; robustness during transportation and lifting, good resistance during vertical and horizontal loading, and durability with fire resistance for framing in residential buildings [3]. Light gauge steel (LGS) off-site construction is based on assembling steel framed panels through several processes in the manufacturing facility on manufacturing tables or computerized numerical control (CNC) machines. These panels are transported to construction site, erected to each other and connected to 3D modules (e.g. bathroom) as well as the floor cassettes that are constructed onsite. The market share of steel in mid-rise residential buildings represents 3 % in UK, 10 to 15 % in USA and Australia, but less than 1 % in Europe [4].

This indicates that the use of light gauge steel (LGS) in off-site construction needs more attention from researchers to fill the gap between research and practice. It should be noted that the practices of using LGS in off-site construction depend considerably on experience of manufacturers and scale of projects. This paper investigates the factors that affect panel configuration in hybrid construction. It also provides a systematic procedure for optimizing the dimension of panels while satisfying the architectural, structural, transportation, and construction requirements.

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II. Literature Review

Off-site construction requires consideration of production, transportation, and installation performance [5]. Design of offsite construction project takes into account the constructability, site logistics and fabrication process. Architectural design requires early collaboration between all potential modular/panel suppliers for adequate planning of these buildings to accommodate any variation in size and layout [1]. The structural design is also controlling the configuration of Off-site construction due to the loads acting on modules during fabrication, transportation and site loadings, as well as long term sustained loads. Lack of specific design, code requirements, and construction guidelines led to the use of finite element modeling [6] and BIM structural processes [7] to design modular and offsite construction buildings. The composite nature of modular and offsite construction cannot be covered using the traditional codes for the structural design of cold formed steel member as AISI (American Iron and Steel Institute code), CISC (Canadian Institute of steel construction), Eurocode 3: design of steel structures, or the British Standards Institute steel code [4]. Hence, other studies discussed serviceability, robustness, and deflection of light steel gauge framing and modular construction by testing full scale modules [4] to illustrate the influence of module configuration on its characteristics. Transportation limitations affect also module/panel configuration to facilitate shipping [8]. Architecture of modular and offsite construction buildings is constrained by manufacturing and transportation requirements which may accommodate some variation in size and layout [1].

The literature highlights the need for a framework that considers the identified constraints to select the most suitable configuration of panelized projects. Hence the proposed method introduces a new framework that assists stakeholders of modular construction projects in selecting the optimized panel configuration while considering the architectural, structural, manufacturing, and transportation constraints.

III. Proposed Method

This paper presents a systematic framework that identifies the optimal module/panel configuration based on architectural, structural, manufacturing, and transportation constraints as illustrated in Fig. 1.

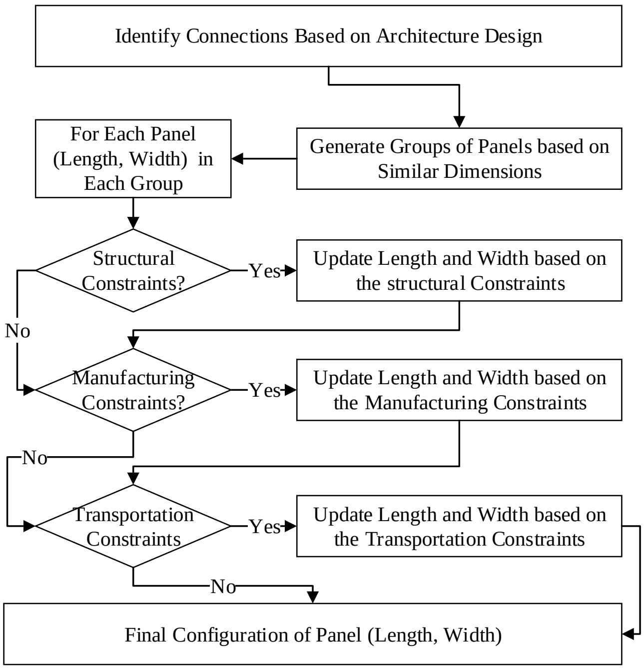

Fig. 1. Systematic framework for most suitable module/panel configuration.

A. *Architectural Design Check*

Building architecture affects considerably the configuration of panels. The hybrid construction approach is based on combining the 3D-modules/units for the high value parts of the building such as kitchens and bathrooms, with the long spanned 2D-panels for the floors and walls in the open areas such as the living rooms and bedrooms. The long span floor cassettes typically span up to 6 meters between separating walls or the sides of the modules [2]. The hybrid construction flexibility in design is gained from the planar nature of panels where any panel dimension can be manufactured to suit the required architectural needs.

There are two main connection types between light steel gauge framing components. The first is the factory production connections and the second is the construction site connections [1]. The onsite wall connections can be classified as well into two main categories; the first is the panel to panel connection and the second is the connection between panels and modular units (i.e. kitchen or bathroom).

Panels connections have different shapes according to the type and location of panel as shown in Table 1. Panels are categorized into ten groups in respect to its location; External panels, interior bearing walls , interior nonbearing walls , party, corridor walls, Plumbing walls, elevator walls (interior and exterior) and mechanical shaft walls.

Based on type of panels and its location the possible connections based on architectural design are located on joints of panel to panel, panel to modular units, corners (internal and externals) as indicates by red circles in Fig. 2. This step identifies the width and length of each panel as per architectural constraints.

$$W_A = \begin{cases} w, & \textit{no architectural constraints} \\ w_A, & \textit{architectural constraints exist} \end{cases}$$

TABLE I: PANEL CATEGORIES

Wall Name	Wall Code	Position	Wall Height
Exterior wall	EX362S162_68-68	External wall (façade)	120.375''
Interior Bearing wall	IN2x362S162_97/6	Internal wall perpendicular to floor joists	120.375''
Interior Non Bearing wall	IN362S162-18/18	Internal wall parallel to floor joists	110.375''
Party wall	IN-362S162-54_PT	Internal wall separating two suites	120.375''
Corridor wall	IN-362S162-68CR	Internal wall between corridor and suites	120.375''
Plumbing wall	IN-600S162_68-PL	Internal wall between bathroom and kitchen but never between suites	102.375'' 1st floor 120.375'' repetitive floor 138.375'' last floor
Exterior Elevator wall	EX800S162-43_EL	Exterior wall for elevator shafts	120.375''
Interior Elevator wall	IN-600S162-68_EL	Interior wall for elevator shafts	120.375''
Exterior Mechanical Shaft wall	EX600S162_68/54 EX600S162_54/43	Exterior wall for Mechanical Shafts beside elevators	120.375''

$$L_A = \begin{cases} l, & \textit{no architectural constraints} \\ l_A, & \textit{architectural constraints exist} \end{cases}$$

where,

w and l represent the initial panel width and length respectively

w_A and l_A represent panel width and length due to architectural constraints

W_A and L_A represent respectively the updated length and width of panel due to architectural constraints.

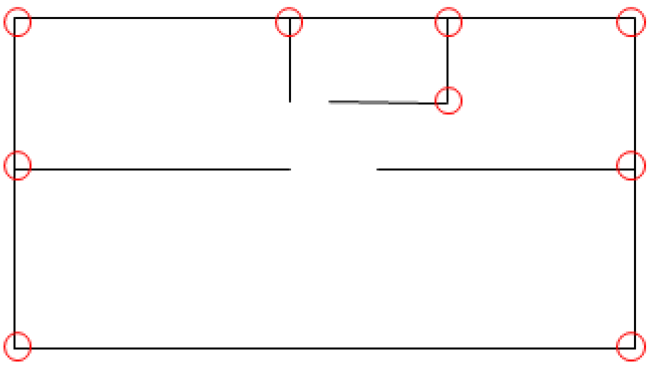

Fig. 2. Identify connections based on architectural design.

B. *Structural Design Check*

Structural design is checked against panel buckling depending on the load sustained by each wall according to the structural design and the position of each panel in the building to identify possible panel length and height. This structural check considers changing panel studs thickness if it is an economical solution or changing panel length.

Light gauge steel framing consists of galvanized steel C-sections of typically 65 to 200mm depth and in steel thicknesses of 1.2 to 2.4mm [9]. Walls are generally pre-fabricated as 2D- storey-high panels and floors are installed as joists or in 2D-cassette form [9].

The hybrid construction building consists of several types of panels according to its location on the building and to the required load it should sustain depending on the structural design of the building. The meaning of wall code (600S162-54) is defined according to the steel stud manufacturers association (SSMA) products report [10]. This code consists of four parts; member depths, style, flange width and material thickness as shown in Fig. 3.

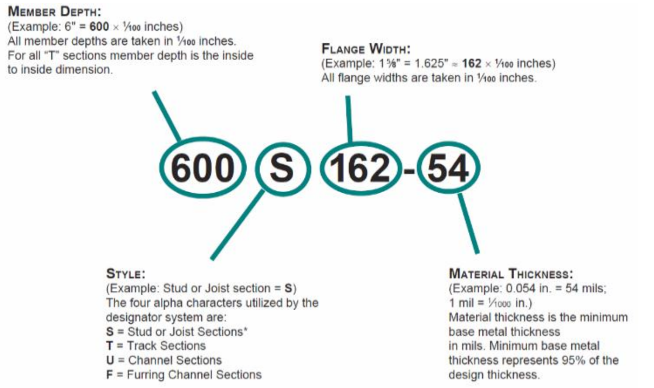

Fig. 3. Product Identification by steel stud manufacturers association (SSMA) [10].

The strength of panels is relative to the steel C-section type/thickness and spacing. The design strength of panels depends on the amount of gravity loads, location of the panel/ module, and lateral load magnitude. The connections between panels must have adequate strength to transfer gravity loads where the bracing elements are supporting panel resistance to lateral load.

Considering the building layout in Fig. 2, and assuming that the length of one or more panels is larger than the allowable length as stated by the standards and regulations. In this case, a new connection should be added to prevent buckling as indicated by the blue circle on Fig. 4.

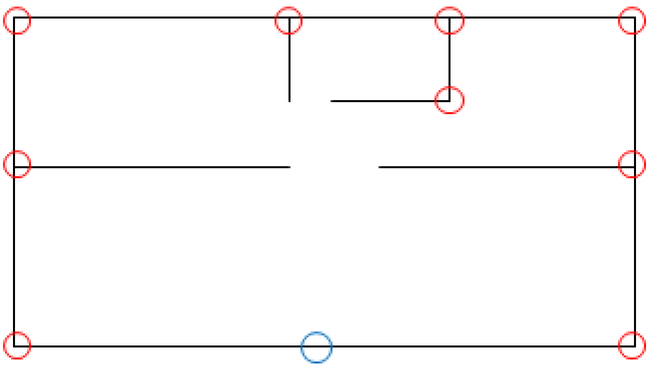

Fig. 4. Identify connections based on Structural design.

Based on structural constraints the length and width of panels are updated as follows:

$$W_{AS} = \begin{cases} W_A, & no\ structural\ constraints \\ w_S, & structural\ constraints\ exist \end{cases}$$

$$L_{AS} = \begin{cases} L_A, & no\ structural\ constraints \\ l_S, & structural\ constraints\ exist \end{cases}$$

where,

w_S and l_S represent panel width and length due to structural constraints

W_{AS} and L_{AS} represent respectively the updated length and width of panel due to architectural and structural constraints.

C. Manufacturing Limitations Check

The next step is to check the limitations of manufacturing facilities to confirm if those facilities have the capacity to produce the required panel size. The production capacity of a manufacturing facility depends on production table or CNC machine size. In this respect, panel dimensions should be less than production table or CNC machines' dimensions. Space limitation is a constraint for the production table's or CNC machines' sizes. Panel sizes are also affected by the automation level followed in any manufacturing facility.

The three main types of manufacturing systems for offsite manufacturing are static, linear, and semi automated linear production [13]. Static production means that the modules/panels are manufactured in one position while all materials and personnel move to the module position [13].

Linear production is a non-automated production line where the manufacturing process is conducted according to different sequential stages similar to the automotive industry [13]. Modules/panels are manufactured on fixed rails and moves between stations. In this type of offsite manufacturing modules/panels moves from a station to another while every station has a dedicated crew working on a specific process on that station.

The semi-automated lines manufacture panels as the linear production system but with highly automated specialized equipment, accompanied with manual operations [13]. For example, semi-automated lines use turning or "butterfly" tables that allows the crews to work on both sides of panels.

Considering the building layout in Fig. 4 and the constraints of manufacturing, other connections should be added as indicated by the blue circles on Fig. 5.

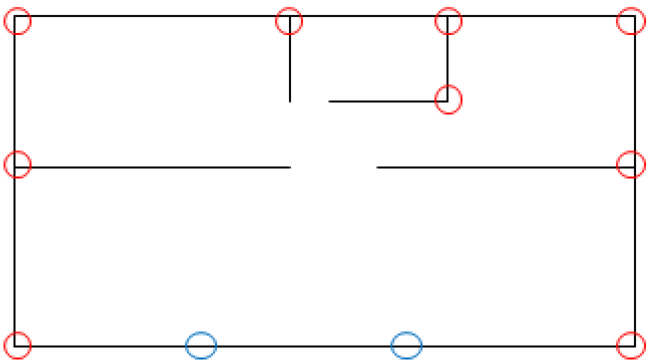

Fig. 5. Identify connections based on manufacturing limitations.

Based on manufacturing constraints the length and width of panels are updated as follows:

$$W_{ASM} = \begin{cases} W_{AS}, & no\ Manufacturing\ constraints \\ w_M, & Manufacturing\ constraints\ exist \end{cases}$$

$$L_{ASM} = \begin{cases} L_{AS}, & if\ no\ Manufacturing\ constraints \\ l_M, & if\ Manufacturing\ constraints\ exists \end{cases}$$

where,

w_M and l_M represent panel width and length due to manufacturing constraints

W_{ASM} and L_{ASM} represent respectively the updated length and width of panel due to architectural, structural and manufacturing constraints.

D. Transportation Limitations Check

Transportation limitation is checked if panels can be accommodated on trailers based on the dimensions of available trailers and the transportation regulations that are usually stipulated by the department of transportation. Hybrid and panelized manufacturing systems are more flexible than modular manufacturing systems and can more easily accommodate variations in plan and detailed design than volumetric systems. Moreover, panelized manufacturing systems can be stacked and transported easier in one truckload due its flat shape as shown in Fig. 8. In contrary, modular construction systems have many constraints in transportation. Though panels' finishes have a greater possibility to be damaged during transportation to the construction site comparing to modular transportation [1]. The transportation trailers for panelized construction are equipped with special steel frames to fix the panels during transportation to reduce panels' damage as shown in Fig. 9. Based on manufacturing constraints the length and width of panels are updated as follows:

$$W_{ASMT} = \begin{cases} W_{ASM}, & no\ Transportation\ constraints \\ w_T, & Transportation\ constraints\ exist \end{cases}$$

$$L_{ASMT} = \begin{cases} L_{ASM}, & if\ no\ structural\ constraints \\ l_T, & if structural\ constraints\ exists \end{cases}$$

where,

w_T and l_T represent panel width and length due to manufacturing constraints

W_{ASMT} and L_{ASMT} represent final length and width of panel due to architectural, structural, manufacturing and transportation constraints

IV. Case Study

The proposed framework was applied on a hybrid construction project in a manufacturing facility in Edmonton Alberta. This project includes fabrication of LGS panels and modular units for residential buildings. This case study is used to demonstrate the applicability of proposed framework and to illustrate its features in selecting the panel dimensions based on architectural, structural, manufacturing and transportation constraints.

A. The Architectural Design

The hybrid residential building is divided into 14 different suites as shown in Fig. 6. Each suite has different plan where the interior panels have different lengths. Though the most common panel length ranges from 10 to 12 feet since this is the regular practical room width. The red circles shown in Fig. 7 indicate the panel connections locations where each room has four onsite connections at its four corners, and this indicates that the common panel length is dominated architecturally by the practical room dimensions.

The studied manufacturing facility manufactures the bathrooms as separate load bearing modules, while the kitchen panels are assembled onsite as a panelized system. The dimensions of the bathroom modules depend on the architecture plan and the number of its accessories. The bathroom dimensions usually are around 9 feet length by 6 feet width. Furthermore, the height of panels in bathroom differs from 102''for the ground floors to 120'' for the repetitive floors and 138'' for the last floor.

B. The Structural Design

The practice of manufacturing facility is to manufacture panels with 16 feet length or less to avoid buckling. However, if the panel length exceeds 16 feet, then the structural design of panel is changed to introduce a new joint that divides the panel being considered into two panels. If the joint is not possible then the manufacturing facility considers the increase of thickness of panel studs to prevent panel buckling. However, increasing the thickness of studs imposes other limitations such as handling on site as well as in the manufacturing facility.

For example, if a 20 feet panel is located in ground floor and it has thickness of studs equals to 97 mils. However, if the same panel is located in the fifth floor that means this panel should have thicker studs since it sustains more loads than the one located in the ground floor. Hence, this panel should better be divided into two panels with 10 feet length and lower studs' thickness (gauge) to be economical for its sustained load, and to be craned and transported without panel buckling.

C. Manufacturing Limitations

The manufacturing process in studied facility integrates static with linear production systems. This process comprises of 3 manual linear tables which are the assembly, framing and sheathing tables. it also comprises eight static racks that allow for performing six sequential processes; waterproofing, foaming, rasping, base coating, priming, and finishing as shown in Fig. 11. The main manufacturing limitation is the framing table that limits the length of panels to 20 feet. This length is actually the maximum length the facility could produce so that the framing crew can handle the framing process properly. The facility manager mentioned that the usual panel dimensions on the eight racks would be 10 feet length by 10 feet height. Though the racks can handle any panel length up to the 20 feet limit.

By applying the proposed framework on the case study layout shown in Fig. 7, most of panel connections were identified based on the architectural design step except for the panel having blue circles. This panel length is 31 feet; hence it was divided by the blue left circle that connects this panel to another perpendicular panel. The remaining of this panel length is 22 feet so it was divided by the right blue circle since the structural design check maximum limit is 16 feet for panel length. Then, manufacturing limitations are already satisfied because all panels have less than 20 feet of length.

TABLE II: Trailers Dimensions

Dimensions	First Trailer	Second trailer
Height from ground level	3' 5''	2' 9''
Length	35'	24' 3''
Width	7' 9''	8'

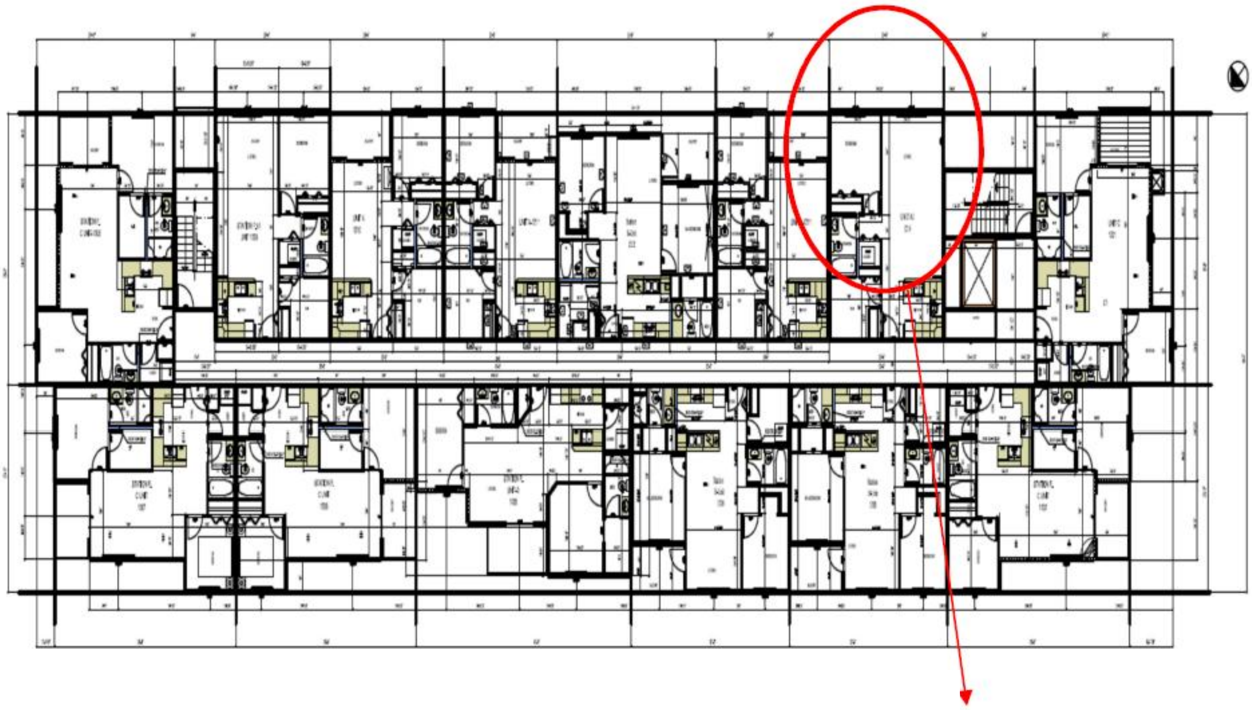

Fig. 6. Different suits in a hybrid construction project layout.

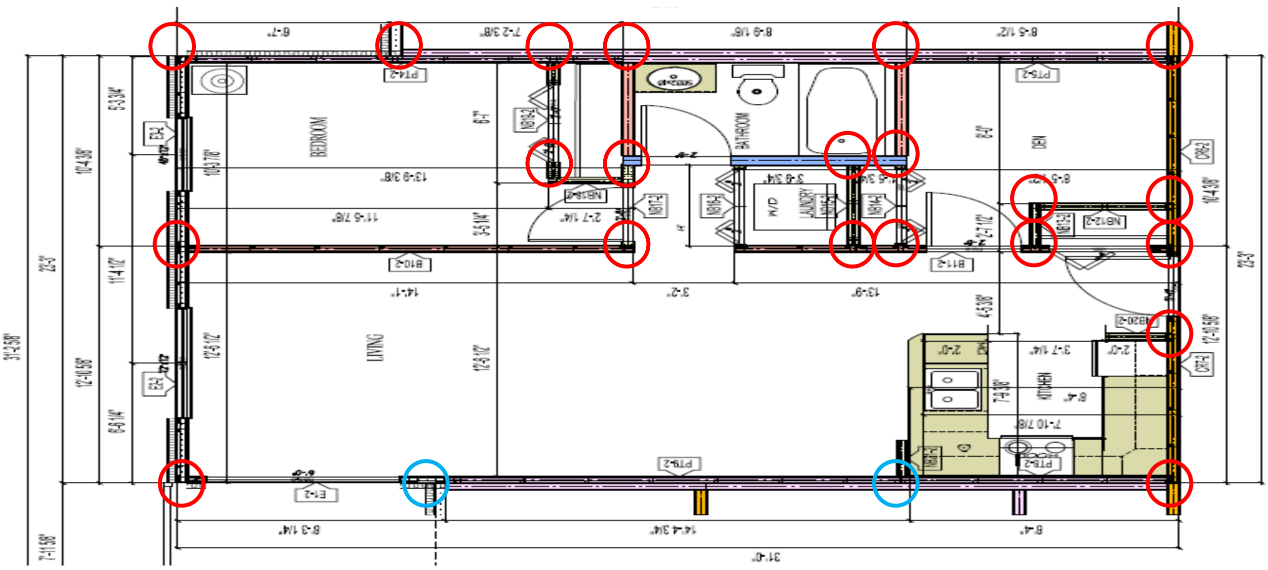

Fig. 7. Separate Suit layout.

Fig. 8. Alignment of panels on trailer.

Fig. 9. Special steel frames on trailer for panel transportation.

Fig. 10. inclined steel frame for last floor parapet panel transportation.

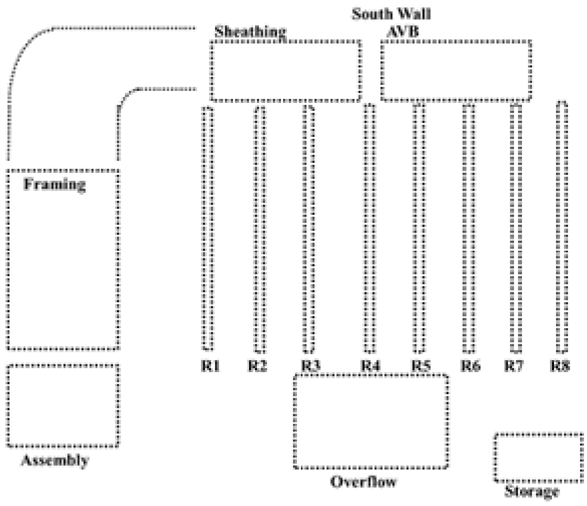

Fig. 11. Manufacturing facility layout.

D. Transportation Limitations

The main transportation limitation for the panels is the trailer height. Since the transportation limitations in Alberta is 13’ 7’’ for trailer height from the ground level, 8’ 6’’ for trailer width, and 75’ 3’’ for the overall maximum trailer length [11]. These transportation limitations are different from a province to another and it is regulated by the department of transportation of each province.

The studied manufacturing facility has three types of trailers according to its dimensions and usage, the trailers dimensions are shown in Table II. The first two trailers dimensions are following Alberta’s transportation limitations regarding the allowable trailer width, but the trailer’s height from ground is restricting the panel height to around 10 feet for the first trailer and around 11 feet for the second trailer. Hence this transportation limitation is usually restricting the building floor height to about 10 feet.

However, the last floor panels’ height would reach 15 or 16 feet due to the parapet extension above the same panels, which cannot be transported using the usual trailers dimensions shown in Table II. Hence this facility is using a third truck with an inclined steel frame as shown in Fig. 10 to facilitate the transportation of the last floor’s panels according to the stipulated height transportation limitation. However, due to inclined shape the number of panels is decreased as compared to trailers 1 and 2.

Moreover, it’s clear that the hybrid and panelized construction are more flexible in transportation than modular construction. Therefore, more manufacturers started to use hybrid construction to eliminate the dimensional limitations that modular manufacturers currently face [12].

V. Conclusion

This paper studied factors that affect the configuration of panels in hybrid construction project. Architectural design dominate the length and width of panels however structural, transportation and manufacturing constraints influence the length and width that exceed the length and width stipulate by regulations and standards. Structural constraints control distortion and buckling of panels during handling and transportation. Transportation constraints limit the trailer truckload height and consequently the width of panels. Manufacturing constraints are related to dimensions of CNC machines and manufacturing tables of the facility. This paper provides a decision support tool that assists stakeholders to select near-optimum dimensions of panels utilized in hybrid construction in accordance with regulations and standards. The proposed framework considers the technical aspects of hybrid construction, but not the economic aspects which may affect further the dimension of panels. In this respect, the integration of technical and economic aspects of hybrid construction project is expected to improve the developed method.

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