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# The optimized form of building made from the reused elements

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## ABSTRACT

A resource-effective society considers a circular economy, and this attitude enters the construction industry as well. Various circular building approaches and strategies are introduced to promote a circular economy. However, the design process is complex because it evolves from available components. To address such a gap, in this article, we address design adjustments with the aim of maximizing the reusing of components from an architectural viewpoint, utilizing an applied research method. To achieve the goal, mathematical programming is suggested to make the best use of available components bearing a system approach in circular design in mind. The objective function is the allocation of reclaimed building materials and the decision variables are the needed components. The issue was categorized as integer nonlinear programming (INLP) solved for global optimality utilizing a genetic algorithm (GA). Design variants define different component allocations; thus, the optimum allocation defines the evolved design. Mathematical programming permits defining component allocation variants and the constraints associated with the project. The result of optimization defines the optimum allocation; consequently, it defines the evolved design. The presented procedure is an innovative method that aims to simplify the complexity associated with adjusting the design based on available components. It promotes procurement efficiency because it makes the best use of available material. Moreover, the minimum energy consumption for transportation due to local material usage leads to reuse efficiency.

## ARTICLE HISTORY

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## KEYWORDS



Sustainability; circular economy; resource efficiency; reuse; means-oriented design

## Highlights

- As optimized form is defined by the optimum allocation, the presented allocation system ease the complexity associated with design adjustment in Means-oriented design approach.
- The allocation is defined as mathematical programming taking the systems approach in circular design into account to control changes.
- The presented method is subjected to parameters defining the objective function.

## Introduction

The building sector consumes 40% of resources, and it is responsible for 33% of human-induced emission and 40% of waste globally (Ness & Xing, 2017). The end-of-life accounts for 50% of

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construction and demolition waste generation (Kibert, 2008) because reutilization is not taken into account in previous phases (Akanbi et al., 2018).

Buildings affect the environment through multiple phase in their life cycle from construction to disposal and their next product system (Sharma, Saxena, Sethi, & Shree, 2011). Energy consumption in the manufacturing process of materials and products, is called embodied carbon. Embodied carbon will account for nearly half of construction emissions by 2050 (IEA, 2018). It is fundamental to decrease the consumption of primary raw materials. It is attainable if we expand the lifespan of goods, and use secondary raw materials produced by waste recycling or reutilization (Huang, et al., 2018). However, the current approach is inefficiently utilizing raw materials. Construction is considered a wasteful industry. New building design assumption is that they will not substantially change for 50–60 years of a lifetime which could result waste of money and carbon. Furthermore, materials and components could be taken into account in terms of permanency though building is not permanent (Gorgolewski, 2018). In order to optimize resource utilization, a closed-loop supply chain will be implemented to extract materials from buildings that are scheduled for demolition (Schultmann & Rentz, 2010). Upcycling plays a crucial role in achieving a closed-loop supply chain and proves to be the most effective approach in minimizing the embodied carbon of a single-family building (Nygaard Rasmussen, Birkved, & Birgisdottir, 2020). The process of upcycling involves transforming old, used, or discarded items into something new and useful (McDonough & Braungart, 2013). In terms of building components, upcycling can be achieved through reuse and recycling. Reuse involves using building components or new materials for a new purpose after dismantling them from a previous building, with little or no additional processing. Recycling, on the other hand, involves reprocessing a component or material to create the same materials or components of the same quality (Sassi, 2008). The reuse approach requires energy for reprocessing, but the energy consumption is significantly lower compared to recycling materials (Hosseini, Rameezdeen, Chileshe, & Lehmann, 2015). With the increasing rate of consumption, recycling alone may not be sufficient to meet future demands (Grosse, 2010).

A noticeable pattern is emerging in the building industry, which aligns with the growing environmental concerns being voiced (Eberhardt, Birkved, & Birgisdottir, 2020). Reuse and recycle are introduced as a part of high-performance green building movement (Kibert, 2016) because they encourage a closed-loop supply chain. The recycling procedure reprocess discarded materials into raw materials aim at producing new products. On the other hand, in the reuse process, discarded components are recirculated and used for the same performance (Thormark, 2000). Component reuse accompanied by some processing is called non-destructive recycling which is a less energy-intensive process to produce components (Smil, 2008).

The reuse approach has a significant impact on the entire construction process, encompassing the design, construction, and demolition stages. It fundamentally challenges the traditional process of structural design by promoting the utilization of existing components and materials. To successfully implement the reuse approach, flexibility in design becomes crucial in order to accommodate the available components (Gorgolewski, 2008). Numerous studies have emphasized the importance of adopting a 'systems approach' when pursuing circular design. This approach entails considering the various system layers, ranging from the planetary scale down to the material scale, while also acknowledging the interrelationships and cohesion with other system layers (Mendoza, Sharmina, Gallego Schmid, Heyes, & Azapagic, 2017; Pieroni, McAlloone, & Pigosso, 2019; Saidani, Yannou, Leroy, & Cluzel, 2017). Two designs for reuse approaches include goal-oriented design and means-oriented design. Goal-oriented design refers to the case where all decisions are targeted at a special purpose. Means oriented design is referred to the case when the design evolves to reuse available materials. The designer, who intends upon Means-oriented design, is dealing with complexity, flexibility, experimentation, and adjustment during design process (Van Hinte, Peeren, & Jongert, 2007). Despite various strategies are implemented in built examples to achieve this integration, designers face difficulties in the design adjusting process.

The Reuse approach reverse the traditional process of structural design, because of predefined properties and accessible elements (Gorgolewski, 2008). There are many feasible allocation variants pursuing a Means-oriented design. Yet, knowledge on how to adapt optimally is lacking.

Focusing on this topic, the general purpose of this article is to ease the process of evolving design to maximize reusing reclaimed building materials in Means-oriented design. Acceptable design layouts according to the flexibility in design are defined. The theory of shearing layers, as a system approach in circular design, is adopted to divide the building into layers. Mathematical programming as a resource manager is used to define different components allocation variants associated with acceptable design layouts. Specific constraints are defined aim to control the compatibility of components while the design is changing. The issue was categorized as integer nonlinear programming (INLP) solved for global optimality utilizing genetic algorithm (GA).

This paper is structured as follows: Section 2 reviews the literature related to circular economy and how it affects the industry, then highlight the research gap. Section 3 gives details regarding the methodology adopted. Section 4 the procedure is implemented in a hypothetical example step by step. Section 5 reports the results and discusses them. Finally, a summation of our findings, limitations and recommendations for future research are presented in the conclusion.

## Literature review

The conflict over natural resources is expected to intensify in the coming decades due to the continuous rise in the global population, which in turn drives the increasing demand for resources (Matthew, Brown, & Jensen, 2009). In general, the main economic model to use resources is linear economy which is attributed to available and cheap materials and energy and waste generation. Linear economy in the construction sector is as follows; extraction of raw materials, transportation, and manufacturing of materials, assembly, use, demolition, and disposal. Physical limitations and repercussions of this model and the urgency of the utilization of the circular economic model were previously realized (Gorgolewski, 2018).

A circular economy aims at closing the loop of an industrial ecosystem and circular flows. The transformation of production and consumption is the core of the circular economy concept (Larsson, 2018), and Decreasing resource consumption, polluted emissions, waste generation, environmental effects, and employment promotion as social advantages are the purposes of circular economy (Dumlao-Tan & Halog, 2017; Ghisellini, Ripa, & Ulgiati, 2018).

### *From a linear to a circular economy*

A linear economy is similar to the flows of a river where the extracted resources turn into base materials and are manufactured through a series of value-adding steps; then, they are prepared for sale (Stahel, 2016). Immense consumption of natural resources and deposition of waste at the end of their life cycle is the result of the linear economy model (Merli, Preziosi, & Acampora, 2018; Stephan & Athanassiadis, 2018). On the contrary, a circular economy or closed loop approach is like a lake that provides the context for narrowing, slowing, and closing material and energy loop, taking regeneration into mind (Geissdoerfer, Savaget, Bocken, & Hultink, 2017).

The practice of using products linearly in the building sector is common (Campbell-Johnston, Cate, & Gupta, 2019). In the present approach of construction practices, materials are cheap and labor is expensive, so most buildings utilize materials wastefully. A more resource-effective proposal requires more design attempts (Gorgolewski, 2018). Landfill and natural resource shortages (Ness, Swift, Ranasinghe, Xing, & Soebarto, 2015) stimulate a reconsideration of conventional practices. Applying circular economy principles is a method to alleviate buildings embodied (Stahel, 2013).

The basic principle of the Circular Economy is efficient resource management (Pomponi & Moncaster, 2017). It focuses on closing and slowing resource loops to make effective use of resources (Bocken, Pauw, Bakker, & van der Grinten, 2016); thus, it eliminates waste and emissions

(Blomsma & Brennan, 2017). This attitude affects the design process because the circular economy aims to maintain product integrity as long as possible over multiple lifecycles.

### *The circular design*

The circular economy aims to narrow, slow, and close the resource loop through Value Retention Processes (VRPs) (Wouterszoon Jansen, van Stijn, Gruis, & van Bortel, 2020). Value retention process (VRPs) implements reuse, repair, refurbish, recycle and recover to narrow, slow and close cycles (Wouterszoon Jansen et al., 2020). Various Circular product design strategies have been introduced to facilitate VRPs (Bakker, den Hollander, Hinte, & Zijlstra, 2014; Moreno, De los Rios, Rowe, & Charnley, 2016; Van den Berg & Bakker, 2015). For example, Beckon proposes six product design strategies to slow loops: (1) design for attachment and trust, (2) design for reliability and durability, (3) design for ease of maintenance and repair, (4) design for upgradability and adaptability, and (6) design for disassembly and reassembly. To close the loop: (7) design for a technological cycle, (8) design for a biological cycle, and (9) design for disassembly and reassembly (Bocken et al., 2016). This approach is implemented aims at product life extension.

The circular economy enters the construction industry as well Numerous strategies are implemented in the construction and demolition phase of a structure to effectively manage resources. These strategies operate, from the planetary scale (building stock) to the material scale. One such strategy is adaptive reuse, which involves retrofitting, rehabilitating, and redeveloping buildings which meet functional requirements (Plevoets & Van Cleempoel, 2011) and the well-being standards according to the existing demands (Bottero, D'Alpaos, & Oppio, 2019). The design process is significantly influenced by adaptive reuse, leading to the advancement of more sophisticated approaches like integral planning and integrative computational design (Leistner et al., 2020). Buildings consist of different components. Designers should consider many design parameters to make building components more circular to address the material scale. Circular design aids help designers through this process. The presented frameworks (Bocken et al., 2016; Lüdeke-Freund, Gold, & Bocken, 2018; Mendoza et al., 2017) state circularity within and beyond the lifecycle should be obtained. Moreover, a system approach is intrinsic to circular design. It permits distinguishing system layers from the planetary scale to the material scale. An integral approach is needed to maintain the coherence of designs in different disciplines (Technical, business, and industrial models). They include the circular design parameters (for example: type of material, the required energy in the use-phase of the component, key partners in the supply chain and the business model, the disassembly process, and the lifecycle stage for each system element) and develop practical design. Every component has its own life cycle but there is interplay with the whole building (Pomponi & Moncaster, 2017). For example, Geldermans (2016) developed a circular design matrix that divides the building into site, structure, skin, setting, service system, and stuff; then, it divides them into components, parts, and materials. Designers take the loop of each element into mind while designing to prevent any weak link. Weak links cause premature obsolete of a larger part or the entire system (Geldermans, 2016).

Various approaches were introduced to facilitate future adaptability in built-environment before the circular economy is conceptualized, for example; open building (Gerritsen, 2015), lean construction (Koskela, 1992), shearing layer (Brand, 1994), and slimbouw (Lichtenberg, 2005). To be more specific, Lean construction as a reaction to economic and environmental inefficiency implements lean manufacturing principles in the construction industry. Production consists of conversions and flows and this attitude affects design, control, and enhancement of production processes. Flow activities should be minimum and conversion activities should be efficient. Three basic flows (design process, material process, and work process) and supporting flows form a construction project (Koskela, 1992).

Various strategies are applied in built examples that attempt to integrate circular design into the built environment; building as a material bank, reusing materials locally, reusing materials on-site, bio-based construction systems, movable container homes, mass-customisable and 'cyclable'

(MCC) building systems, Modular mass-customisable and 'cyclable' (MMCC) building systems, Circular stuff (van Stijn, 2023).

The Reuse approach reverse the traditional process of structural design. Design building with reused component should be flexible to accommodate available reclaimed components (Gorgolewski, 2008). Two approaches to design from the reused elements: goal-oriented design and means-oriented design. Goal-oriented design refers to the case where all decisions are made to achieve a specific purpose. In means-oriented design, the design evolves to reuse available materials. Means-oriented design involves; complexity, flexibility, experimentation, and adjustment during the design process (Van Hinte et al., 2007).

Various strategies and guidelines are proposed to reclaim components. However, a method to facilitate the design adjustment process is still lacking.

Since local material usage is a significant factor in efficient reuse to reduce energy consumption due to minimum transportation (Van Hinte et al., 2007) and the complexity associated with adjustment during the design process, a procedure is required to define an optimal resource allocation. The optimal resource allocation would define the evolved design.

## Research methodology

The utilized type of methodology was applied. Applied research deals with practical problems encountered by an individual, society, and industrial or business organization, and its main purpose finds a solution for a considerable practical problem (Kothari, 2004). The issue is confronted with an evolving design according to available components aimed at maximizing the reuse of reclaimed building materials (Van Hinte et al., 2007).

The complexity of the constraints associated with reusing reclaimed building materials includes is due to size, predefined properties, and number of available stocks (Iacovidou & Purnell, 2016).

The allocation of reclaimed building materials would define a set of resource allocation variants, each of which describes a specific design. The best allocation is the one that uses available stocks and supplies the new requirements the most. Therefore, it describes the optimized evolved design according to available stock. The research goal is to develop an allocation system that aims to maximize the reuse of available stock according to the new design with special functional requirements. Optimization addresses a sort of problem where one or more objectives as functions defined by some real or integer variables have to be maximized or minimized (Bandyopadhyay & Saha, 2012). The purpose is defined as mathematical programming taking a system approach in building into consideration to solve an optimization problem with objective function and constraints. The objective function is the reuse of salvaged or reclaimed building materials and the decision variables are the needed component in new design. The constraints are the number of available materials in a specific project. The systematic relationship among different subsystems in a building is considered to define constraints to control changes in different layers.

### A systems approach in circular design

Studies have showed that making circular design requires a 'systems approach'. A systems approach means we should distinguish system-layer from the planetary scale to the material scale meanwhile the cohesion and relation with other system layers should always be considered (Mendoza et al., 2017; Pieroni et al., 2019; Saidani et al., 2017). It ensures that no rebound effects are made or environmental burdens are shifted from one system to the next one (van Stijn, 2023). The spectrum of design in built environment is from the supranational layer to the material layer. These system layers are divided into specializations, such as architect, building construction specialist, interior designer, window-frame designer, etc. Each of the elements of the building system has its own characteristics and lifespan, but are joint to each other (Brand, 1994). Section 3.1.1 discusses Shearing Layers as an example of Systematic design approach to elaborate the concept.

**Theory of shearing layers**

Stewart Brand (Brand, 1994) proposed that a building becomes adapted when it is constantly adjusted by its occupants and the architect facilitates this process. Also, he stated that the architect should be the artist of time rather than space. They take the conceptual model of layers in a building into account each of which serves in different timescales as shown in Figure 1. They can be replaced and maintained to meet occupants’ needs. Table 1 shows building layers and lists the components related to each layer.

As Brand (Brand, 1994) said, lifespan connection is apparent in subsystems within the mentioned layers.

**Optimization formulation**

Reusing reclaimed building materials can be defined as the optimization issue to maximize the reclamation of accessible components as decision variables. The optimization problem refers to selecting n decision variables  $x_1, x_2, x_3, \dots, x_n$  ( $x_i \in Z^n$ ) from a given feasible region so as to optimize a given objective function defined by decision variables as shown in Equation (1).

$$F(x_1, x_2, x_3, \dots, x_n) \tag{1}$$

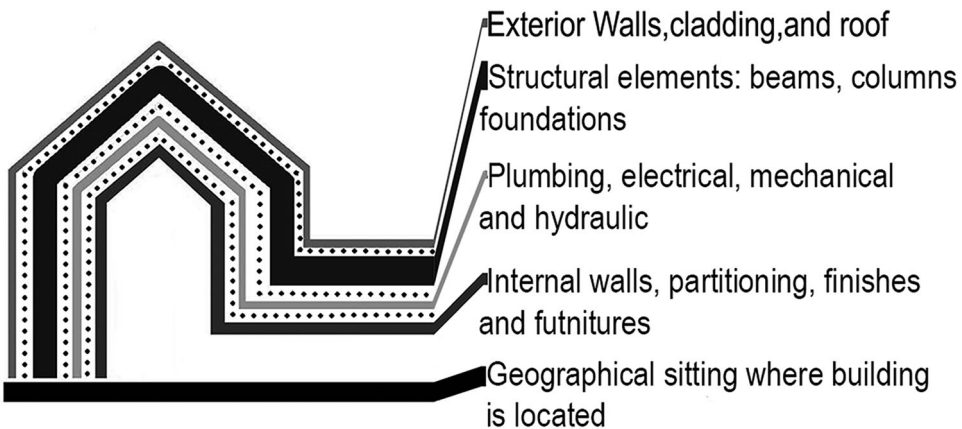
A branch of optimization theory is mathematical programming where an objective performance defined by n real variables  $x_1, x_2, x_3, \dots, x_n$  which perhaps subjected to limitations in inequalities or equations is minimized or maximized (Avriel, 2003). Equation (2) denote the required components in each layer, by  $x_1, x_2, x_3, \dots, x_n$ :

$$\text{Reuse}(x) = \left[ \sum_{i=1}^n x_{i\text{structure}} + \sum_{i=1}^n x_{i\text{skin}} + \sum_{i=1}^n x_{i\text{service}} + \sum_{i=1}^n x_{i\text{space plan}} \right] \tag{2}$$

The required components in each layer are components of column vector identified by mathematical programming to please limitations as indicated in Equation (3).

$$F(\text{component}) = \sum_{i=1}^n \sum_{j=1}^m C_{ij}x_{ij} = \begin{bmatrix} c_{11} & \dots & c_{1j} \\ \vdots & \ddots & \vdots \\ c_{i1} & \dots & c_{ij} \end{bmatrix} * \begin{bmatrix} x_{11} \\ x_{21} \\ \vdots \\ x_{i1} \end{bmatrix} \tag{3}$$

The following constraints should be seen:



**Figure 1.** Brand’s 6S Shearing layers theory. Adapted from Brand (1994). The thickness of lines shows the longevity of layers.

**Table 1.** Building layers. Adapted from Brand (1994).

Building layers	Component
Layer 5: stuff	Movable items around the building
Layer 4: space plan	Internal walls, partitioning, finishes and furniture
Layer 3: service	Plumbing, electrical, mechanical and hydraulic
Layer 2: skin	Exterior walls, cladding and roof
Layer 1: structure	Structural elements: beams, columns, foundations
Layer 0: site	Site geographical sitting where building is located

- Due to accessible components' and constraints associated with reuse on-site, the sum of the allocated components should not exceed accessible stock.
- One supplier must be selected as the final supplier among acceptable suppliers.
- Flexibility in the design must be controlled in each layer to reach a final synchronization.

Regarding the discussion above, the optimum design problem can be noted using a mathematical programming problem.

Due to the accessible reclaimed building materials and limitations on design changes, the number of feasible acceptable structural plan layouts is limited which could be described using mathematical programming. Length is a shared property in different layers to control the maximal reuse, so the mentioned property is considered in the objective function definition. There are two associated limitations in the allocation process; the number of accessible elements and the one and only final chosen supplier.

The selection of suitable components from several accessible components can be shown by a matrix shown in Equation (3). its inputs are:

$$C_{ij} = u_{ij} * l_{ij}$$

$U = 1$  if an element of group  $j$  is assigned to position  $i$ .

$U = 0$  if an element of group  $j$  is not assigned to position  $i$ .

$L$  = the length of the component. Length is taken into account aiming at controlling the maximal reuse.

The total number of entries  $u_{ij}$  in every row should be one to ensure the assignment of one stock component as a final supplier in design. These constraints of choosing a final supplier could be satisfied using Equation (4).

$$\sum_{j=1}^m u_{ij} \leq 1 \quad \forall i = 1, \dots, n$$

$$u_{ij} \in \{0, 1\} \quad \forall ij$$
(4)

Every column of the assignment matrix corresponds to a stock element group. The total number of entries in every column demand must be equal or smaller to the number  $n_j$  of on hand elements in the final chosen supplier. The constraint of accessible material could be satisfied using Equation (5).

$$\sum_{i=1}^n x_{ij} \leq n_j$$

$$\forall j = 1, \dots, m$$
(5)

Take the system approach in building into account, that there are internal connections among different components in each layer that could be controlled by their special properties. For instance, load carrying capacity of structural elements is defined according to tributary width. The façade system depends on the dimension of the overall structure of the building, and mechanical system properties are ascribed by the volume identified by structural and interior design. The

forementioned connection could be considered as a constraint to control changes in different layers. The overall surface of a building covered by the façade system should be matched with the length of the covered structure. The length is the shared property in the structure subsystem and façade subsystem. The constraint could be satisfied using Equation (6).

$$(x_1 L_{\text{type } 1}) + (x_2 L_{\text{type } 2}) + \dots + (x_n l_{\text{type } n}) \leq L_{\text{overall correspond structure}} \quad (6)$$

Decision variables of required panels are denoted by  $x_{ij}$ , and  $l_{ij}$  is the length of panels. The final design among resource allocation variants will be the one which satisfies maximization reuse goal as an objective function.

There are allocation alternatives to reuse salvaged or reclaimed building materials each of them describes a specific design. The objective function aims at maximizing the reuse of reclaimed building material; therefore, this procedure cuts the complexity associated with evolving design. The decision variables are the required components and constraints are the number of available component components. Subgroups of the elements affect the entire system; therefore, constraints are defined to control changes in different layers, taking the Systematic design approach into account.

One or more nonlinear functions in mathematical programming will be defined it nonlinear programming (Avriel, 2003). Decision variables are discrete; hence, it is an integer programming problem (IP) (Wolsey, 1998). The optimization problem is described as an integer nonlinear programming (INLP) problem it can be solved for global optimality by employing a genetic algorithm (GA). GAs are a heuristic solution search or optimization method, inspired by Darwinism, theory of biological evolution through (genetic) selection (McCall, 2005). GA is derived from survival of the fittest, which combines genetic operations originating from nature. GA provides the context for solving complex nonlinear optimization problems efficiently. It is a certified tool to define a useful solution for optimization (Goldberg, 1989). The Mathematical programming presented in this article was solved using a GENETIC solver. MATLAB software is used to Model the problem. MATLAB software provides a genetic algorithm solver for mixed-integer or continuous-variable optimization problems, either constrained or unconstrained.

## Data analysis

Figures 2 and 3 show two plans, different in some areas which are considered hypothetical examples. The existing building needs some changes in some areas to adapt to new use. Considering acceptable design flexibility, design variants are determined to figure out the required materials. Then, resource allocation is described using mathematical programming and the best design mode is chosen aiming at maximal usage of available materials.

The new building will be built using the available components on site. Table 2 lists the available stock that could be used in the new building. The building comprises of steel structural system containing beams and columns and a Facade system that contains an aluminum macro-panel frame and cladding panels. There are three types of beams different in length. The load-carrying capacity of beams with the same length is the same, and it is equal to the loaded beam which carries the largest tributary width in the plan. The load-carrying capacity of every column is equal to the Tributary width where the column is loaded.

There are three types of beams, eight types of columns, which are different in load-carrying capacity, and two types of aluminum macro-panel frame and cladding panels which are fitted to dimensions of related structural elements.

Assumptions for Reuse and Stock (Gerritsen, 2015):

- A stock of the reclaimed structural elements is on hand without any defects and attached joints allow their connection.
- The structural capacity of columns could be amplified to 10%.
- Half of the load-carrying capacity of columns could be loaded.

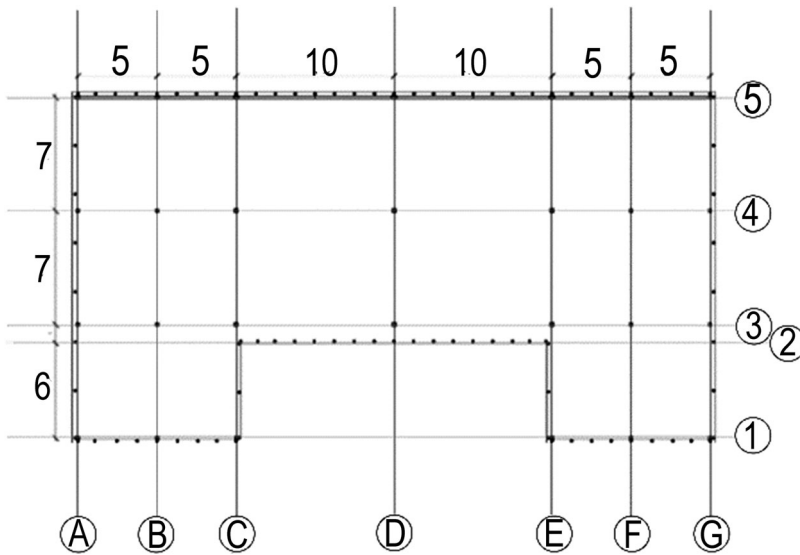


Figure 2. Built building.

Flexibility in design is an underlying necessity in the reuse approach. Take Figure 3. Into mind, the overall length in the span of 7-4 is allowed to get longer within 2 m. The span of A-C is not flexible due to design constraints. The skin layer is composed of two different types of aluminum macro-panel frames and cladding panels. The façade layout is flexible within 4 m in span of 7-4 in aux C

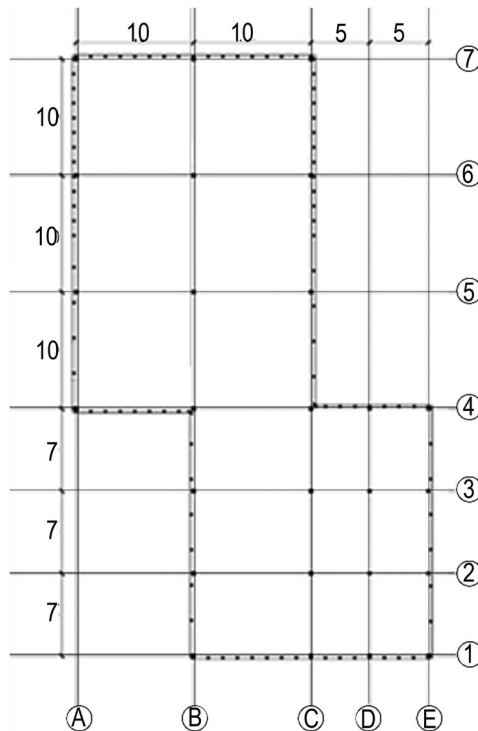


Figure 3. New building plan. This plan was presented after some changes in the extant building.

**Table 2.** Available stock.

New requirements	Type	Quantity	Length	Height	The tributary area
Beam	1	8	5	–	35/2
	2	11	7	–	35/4 + 70/4
	3	4	10	–	70/4 + 70/4
Column	1	3	4	–	2.5*3.5
	2	2	4	–	7*2.5
	3	2	4	–	5*3.5
	4	2	4	–	7.5*3.5
	5	2	4	–	5*7
	6	2	4	–	7*7.5
	7	2	4	–	3.5*10
	8	1	4	–	7*10
Facade Cladding	1	11	3	4	–
	2	14	2.5	4	–

and A. Besides the mentioned design flexibility, the existing building restricts the changes. The new part of the building is connected to the previously built part in aux 4 and the span of B-C. Figure 4 shows design variants considering design flexibility and available components.

The first layer as described in Equation (7), contains structural elements: beams, columns, foundations.

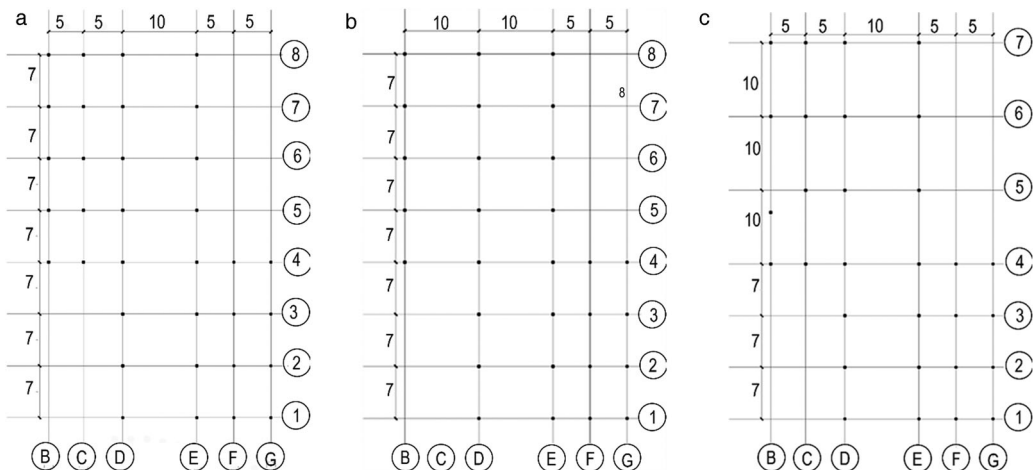
$$\text{Reuse(structure)} = \sum_{i=1}^n n_{\text{beams type } i} + \sum_{i=1}^n n_{\text{columns type } i} + \sum_{i=1}^n n_{\text{foundations type } i} \quad (7)$$

Table 3 lists the requirements to construct the first alternative and suitable stock to supply the requirement according to length, Tributary width, load-carrying capacity, and structural enhancement.

From Equation (3), we obtain the beam allocation according to the new requirement which is given in Equation (8). The length was considered in the objective function definition to maximize usage.

$$F(\text{beam}) = \sum_{i=1}^3 \sum_{j=1}^3 C_{ij}x_{ij} = u_{11}l_{11}x_{11} + u_{22}l_{22}x_{22} + u_{33}l_{33}x_{33} \quad (8)$$

Decision variables of required beams are denoted by  $x_{ij}$ ;  $l_{ij}$  is the length of allocated beams, and  $u_{ij}$  is the feasibility of beam allocation according to component properties. From Equation (3), we obtain



**Figure 4.** Feasible structural plans according to available stock and restrictions on changes.

the column allocation according to the new requirement which is given in Equation (9). The length was considered in the objective function definition to maximize usage.

$F(\text{column}) =$

$$\sum_{i=1}^8 \sum_{j=1}^6 C_{ij}x_{ij} = u_{14} l_{14}x_{14} + u_{22}l_{22}x_{22}+u_{23}l_{23}x_{23}+u_{32}l_{32}x_{32}+ u_{33}l_{33}x_{33}+ u_{42}l_{42}x_{42} + u_{43}l_{43}x_{43}+ u_{51}l_{51}x_{51} + u_{56}l_{56}x_{56}+ u_{61}l_{61}x_{61}+ u_{65}l_{65}x_{65} + u_{66}l_{66}x_{66} + u_{71}l_{71}x_{71} + u_{76}l_{76}x_{76}+ u_{85}l_{85}x_{85} \tag{9}$$

Decision variables of needed columns are denoted by  $x_{ij}$ ;  $l_{ij}$  is the length of allocated columns, and  $u_{ij}$  is the feasibility of columns allocation due to component properties. The constraints to choose a final supplier could be satisfied using Equation (4) which is given in Equation (10):

$$\begin{aligned} u_{51} + u_{61} + u_{71} &\leq 1 \\ u_{22} + u_{32} + u_{42} &\leq 1 \\ u_{23} + u_{33} + u_{43} &\leq 1 \\ u_{65} + u_{85} &\leq 1 \\ u_{56} + u_{66} + u_{76} &\leq 1 \end{aligned} \tag{10}$$

The total number of entries in every column demand must be equal or smaller to the number  $n_j$  of on hand elements in chosen supplier. The aforementioned constraint could be satisfied using Equation (5) which is given in Equation (11):

$$\begin{aligned} x_{14} &\leq 3 \\ x_{22} + x_{23} &\leq 2 \\ x_{32} + x_{33} &\leq 2 \\ x_{42} + x_{43} &\leq 2 \\ x_{51} + x_{56} &\leq 2 \\ x_{61} + x_{65} + x_{66} &\leq 2 \\ x_{71} + x_{76} &\leq 2 \\ x_{85} &\leq 1 \end{aligned} \tag{11}$$

Table 4 lists the need to construct the second alternative and suitable stock to supply the requirement according to length, tributary width, load carrying capacity, and permitted structural enhancement.

**Table 3.** The requirements to construct the first option.

New requirements	Type	Length	Quantity	The tributary area	Suitable stock	Suitable stock (1:2 Structural Capacity)
Beam	1	5	4	35/4	Type 1	–
	2	5	6	35/2	Type 1	–
	3	7	4	35/4	Type 2	–
	4	7	4	35/4 + 35/4	Type 2	–
	5	7	4	70/4 + 35/4	Type 2	–
	6	7	4	70/4	Type 2	–
	7	10	4	70/4 + 70/4	Type 3	–
	8	10	1	70/4	Type 3	–
Column	1	4	3	5*7	Type5, Type7	Type6
	2	4	3	7*2.5	Type2, Type3	Type4
	3	4	2	5*3.5	Type2, Type3	Type4
	4	4	2	2.5*3.5	Type1	–
	5	4	3	7*7.5	Type6	Type8
	6	4	3	7*5	Type5, Type7	Type6

From Equation (3), we obtain the beams allocation according to the new requirement which is given in Equation (12). The length was considered in the objective function definition to maximize usage.

$$F(\text{beam}) = \sum_{i=1}^3 \sum_{j=1}^2 C_{ij}x_{ij} = u_{21}l_{21}x_{21} + u_{32}l_{32}x_{32} \tag{12}$$

Decision variables of required beams are denoted by  $x_{ij}$ ;  $l_{ij}$  is the length of allocated beams, and  $u_{ij}$  is the feasibility of beam allocation due to component properties. From Equation (3), we obtain the columns allocation according to the new requirement which is given in Equation (13). The length was considered in the objective function definition to maximize usage.

$$F(\text{column}) = \sum_{i=1}^8 \sum_{j=1}^4 C_{ij}x_{ij} = u_{21}l_{21}x_{21} + u_{31}l_{31}x_{31} + u_{41}l_{41}x_{41} + u_{52}l_{52}x_{52} + u_{53}l_{53}x_{53} + u_{62}l_{62}x_{62} + u_{63}l_{63}x_{63} + u_{72}l_{72}x_{72} + u_{73}l_{73}x_{73} + u_{84}l_{84}x_{84} \tag{13}$$

Decision variables of needed columns are denoted by  $x_{ij}$ ,  $l_{ij}$  is the length of allocated columns, and  $u_{ij}$  is the feasibility of column allocation according to component properties. The constraints to choose a final supplier could be satisfied using Equation (4) which is given in Equation (14):

$$\begin{aligned} u_{21} + u_{31} + u_{41} &\leq 1 \\ u_{52} + u_{62} + u_{72} &\leq 1 \\ u_{53} + u_{63} + u_{73} &\leq 1 \end{aligned} \tag{14}$$

The total number of entries in every column demand must be equal or smaller to the number  $n_j$  of on hand elements in the chosen supplier. The supply constraint could be satisfied using Equation (5) which is given in Equation (15):

$$\begin{aligned} x_{21} &\leq 3 \\ x_{31} &\leq 2 \\ x_{41} &\leq 2 \\ x_{52} + x_{58} &\leq 2 \\ x_{62} + x_{63} &\leq 2 \\ x_{72} + x_{73} &\leq 2 \\ x_{84} &\leq 1 \end{aligned} \tag{15}$$

Table 5 lists the requirements to construct the third alternative and reclaimed building material to supply the requirement according to the length, tributary width, load carrying capacity, and structural enhancement.

**Table 4.** The requirements to construct the second option.

New requirements	Type	Length	Quantity	The tributary area	Suitable stock	Suitable stock (1:2 Structural Capacity)
Beam	1	7	8	35/4	Type 2	–
	2	7	4	35/4 + 35/4	Type 2	–
	3	10	6	35/4 + 35/4	Type 3	–
	4	10	3	35/4	Type 3	–
	5	10	1	35/2	Type 3	–
Column	1	4	3	5*3.5	Type2, Type3	Type4
	2	4	2	10*3.5	Type5, Type7	Type6
	3	4	6	7*5	Type5, Type7	Type6
	4	4	3	7*10	Type8	–

From Equation (3), we obtain the beams allocation according to the new requirement which is given in Equation (16). The length was considered in objective function definition to maximize usage.

$$F(\text{beam}) = \sum_{i=1}^3 \sum_{j=1}^2 C_{ij} x_{ij} = u_{11} l_{11} x_{11} + u_{32} l_{32} x_{32} \quad (16)$$

Decision variables of needed beams are denoted by  $x_{ij}$ ;  $l_{ij}$  is the length of allocated beams, and  $u_{ij}$  is the feasibility of beam allocation according to component properties. From Equation (3), we obtain the columns allocation according to the new requirement which is given in Equation (17). The length was considered in the objective function definition to maximize usage.

$$F(\text{column}) = \sum_{i=1}^8 \sum_{j=1}^7 C_{ij} x_{ij} = u_{21} l_{21} x_{21} + u_{31} l_{31} x_{31} + u_{42} l_{42} x_{42} + u_{46} l_{46} x_{46} + u_{57} l_{57} x_{57} + u_{63} l_{63} x_{63} + u_{65} l_{65} x_{65} + u_{77} l_{77} x_{77} + u_{83} l_{83} x_{83} + u_{84} l_{84} x_{84} + u_{85} l_{85} x_{85} \quad (17)$$

Decision variables of needed columns are denoted by  $x_{ij}$ ;  $l_{ij}$  is the length of allocated columns, and  $u_{ij}$  is the feasibility of column allocation due to component properties. The aforementioned constraint could be satisfied using Equation (4) which is given in Equation (18):

$$\begin{aligned} u_{21} + u_{31} &\leq 1 \\ u_{63} + u_{83} &\leq 1 \\ u_{65} + u_{85} &\leq 1 \\ u_{57} + u_{77} &\leq 1 \end{aligned} \quad (18)$$

The total number of entries in every column demand must be equal or smaller to the number  $n_j$  of on hand elements in chosen supplier. The supply constraint could be satisfied using Equation (5) which

**Table 5.** The requirements to construct the third option.

New requirements	Type	Length	Quantity	The tributary area	Suitable stock	Suitable stock (1:2 Structural Capacity)	Suitable stock (1.1:1 Structural Capacity)
Beam	1	5	4	50/4 + 50/4	–	–	–
	2	5	3	50/4	Type 2	–	–
	3	10	3	50/4	Type 3	–	–
	4	10	3	50/4 + 50/4	Type 3	–	–
	5	10	3	50/4 + 100/4	–	–	–
	6	10	3	100/4	Type 3	–	–
	7	10	3	100/4 + 100/4	–	Type6	–
	8	10	1	100/4	Type 3	–	–
Column	1	4	2	2.5*5	–	Type2, Type3	–
	2	4	2	2.5*10	–	Type4	–
	3	4	2	10*5	–	Type6	Type8
	4	4	2	7.5*10	–	–	Type8
	5	4	2	10*5	–	Type6	Type8
	6	4	3	5*5	–	Type4	–
	7	4	2	7.5*5	–	–	Type5, Type7

is given in Equation (19):

$$\begin{aligned}
 x_{21} &\leq 2 \\
 x_{31} &\leq 2 \\
 x_{42} + x_{46} &\leq 2 \\
 x_{57} &\leq 2 \\
 x_{63} + x_{65} &\leq 2 \\
 x_{72} + x_{73} &\leq 2 \\
 x_{83} + x_{84} + x_{85} &\leq 1
 \end{aligned}
 \tag{19}$$

After determining different possible designs using reclaimed building material, we need to select the optimum one. There are three resource allocation variants pursuing Means-oriented design and one of them would be the final choice according to objective function which was previously noted as the optimum structure plan aiming to maximize reuse of available components. The aforementioned inconsistency is described in Equation (20):

$$\begin{aligned}
 F(\text{component}) &= \sum_{i=1}^3 \omega_i z_i \\
 \sum_{i=1}^m \omega_i &= 1 \\
 \omega_i &\in \{0, 1\} \quad \forall i
 \end{aligned}
 \tag{20}$$

Decision variables of structural design alternatives are denoted by  $\omega_i$  and  $z_i$  is the feasible structural alternatives identified according to design flexibility, used in Equation (21):

$$\begin{aligned}
 &\omega_1 \left[ (u_{11}l_{11}x_{11} + u_{22}l_{22}x_{22} + u_{33}l_{33}x_{33}) \right. \\
 &\quad \left. + \left( \begin{aligned} &u_{14}l_{14}x_{14} + u_{22}l_{22}x_{22} + u_{23}l_{23}x_{23} + u_{32}l_{32}x_{32} + u_{33}l_{33}x_{33} + u_{42}l_{42}x_{42} + u_{43}l_{43}x_{43} + u_{51}l_{51}x_{51} \\ &u_{56}l_{56}x_{56} + u_{61}l_{61}x_{61} + u_{65}l_{65}x_{65} + u_{66}l_{66}x_{66} + u_{71}l_{71}x_{71} + u_{76}l_{76}x_{76} + u_{85}l_{85}x_{85} \end{aligned} \right) \right] \\
 &+ \omega_2 \left[ (u_{21}l_{21}x_{21} + u_{32}l_{32}x_{32}) + \left( \begin{aligned} &u_{21}l_{21}x_{21} + u_{31}l_{31}x_{31} + u_{41}l_{41}x_{41} + u_{52}l_{52}x_{52} + u_{53}l_{53}x_{53} + u_{62}l_{62}x_{62} \\ &+ u_{63}l_{63}x_{63} + u_{72}l_{72}x_{72} \\ &u_{73}l_{73}x_{73} + u_{84}l_{84}x_{84} \end{aligned} \right) \right] \\
 &+ \omega_3 \left[ (u_{11}l_{11}x_{11} + u_{32}l_{32}x_{32}) + \left( \begin{aligned} &u_{21}l_{21}x_{21} + u_{31}l_{31}x_{31} + u_{42}l_{42}x_{42} + u_{46}l_{46}x_{46} + u_{57}l_{57}x_{57} \\ &u_{63}l_{63}x_{63} + u_{65}l_{65}x_{65} + u_{77}l_{77}x_{77} + u_{83}l_{83}x_{83} + u_{84}l_{84}x_{84} + u_{85}l_{85}x_{85} \end{aligned} \right) \right]
 \end{aligned}
 \tag{21}$$

Decision variables of needed components are denoted by  $x_{ij}$ ;  $l_{ij}$  is the length of allocated components, and  $u_{ij}$  is the feasibility of components allocation due to their properties.

The existing building is incomplete and requires components to be completed. Table 6 lists the requirements of the left area (in Span of 1–4 aux B, according to Figure 3) in Layer1 structure sub-system which includes beams and columns.

From Equation (3), we obtain the beam allocation according to the new requirement which is given in Equation (22). The length was considered in the objective function definition aiming to maximize usage.

$$F(\text{beam}) = \sum_{i=1}^3 \sum_{j=1}^2 C_{ij} x_{ij} = u_{21}l_{21}x_{21} + u_{32}l_{32}x_{32}
 \tag{22}$$

Decision variables of required beams are denoted by  $x_{ij}$ ;  $l_{ij}$  is the length of allocated beams, and  $u_{ij}$  is the feasibility of beam allocation due to component properties. From Equation (3), we obtain the

columns allocation according to the new requirement which is given in Equation (23). The length was considered in the objective function definition aiming to maximize usage.

$$F(\text{column}) = \sum_{i=1}^8 C_{i1} x_{i1} = u_{21} l_{21} x_{21} + u_{31} l_{31} x_{31} + u_{41} l_{41} x_{41} \quad (23)$$

Decision variables of required columns are denoted by  $x_{ij}$ ,  $l_{ij}$  is the length of allocated columns, and  $u_{ij}$  is the feasibility of column allocation according to component properties. The constraint to choose one supplier could be satisfied using Equation (4) which is given in Equation (24):

$$u_{21} + u_{31} + u_{41} \leq 1 \quad (24)$$

The total number of entries in every column demand must be equal or smaller to the number  $n_j$  of on hand elements in chosen supplier. The supply constraint could be satisfied using Equation (5) which is given in Equation (25):

$$\begin{aligned} x_{21} &\leq 2 \\ x_{31} &\leq 2 \\ x_{41} &\leq 2 \end{aligned} \quad (25)$$

The second layer which is described in Equation (26), is the skin subsystem and contains exterior wall, cladding, and roof. Figures 5–8. Show façade system layout and available stock in the second layer take the new design Figure 3 into account.

$$\text{Reuse}(\text{skin}) = \sum_{i=1}^n n_{\text{exterior wall type } i} + \sum_{i=1}^n n_{\text{cladding type } i} + \sum_{i=1}^n n_{\text{roof type } i} \quad (26)$$

The skin subsystem of the hypothetical example, the façade system comprises of aluminum macro-panel frame and cladding panel elements. There are two various types of aluminum macro-panel frames and cladding panels. Table 7 lists the design requirements for skin taking the allowed flexibility in design into account.

The assignment according to new requirements in the façade system is noted in Equation (27). The length was considered in the objective function definition to maximize usage.

$$\begin{aligned} F(\text{cladding}) &= \sum_{i=1}^3 \sum_{j=1}^2 C_{ij} x_{ij} \\ &= u_{11} l_{11} x_{11} + u_{13} l_{13} x_{13} + u_{22} l_{22} x_{22} + u_{24} l_{24} x_{24} + u_{25} l_{25} x_{25} + u_{26} l_{26} x_{26} \end{aligned} \quad (27)$$

Decision variables of needed cladding panel elements are denoted by  $x_{ij}$ ;  $l_{ij}$  is the horizontal length of allocated cladding panels, and  $u_{ij}$  is the feasibility of cladding allocation according to component properties. The total number of entries in every column demand must be equal to or smaller than the number  $n_j$  of on hand elements in the corresponding supplier. The supply constraint could

**Table 6.** Structural requirements of the left area Span 1–4 aux D.

New requirements	Type	Length	The tributary area	Quantity	Suitable stock (1:2 Structural Capacity)	Suitable stock	Suitable stock (1.1:1 Structural Capacity)
Beam	1	7	70/4	1	–	Type2	–
	2	10	70/4	1	–	Type3	–
Column	1	4	5*3.5	1	Type4	Type2, Type3	–

**Table 7.** The skin layer the requirement.

New requirements	Span	Overall length	Dimensions (length * height)	Right on design	Shift to right	Shift to left
1	Span4-7 aux A	15	3*4	type1*5	type1*4	type1*6
2		15	2.5*4	type1*6	type2*5	type2*4
3	Span 4-7 aux C	15	3*4	type1*5	type1*4	type1*6
4		15	2.5*4	type2*6	type2*5	type2*7
5	Span AB aux4	10	2.5*4	type2*4	-	-
6	Span AC aux7	20	2.5*4	type2*8	-	-

be satisfied using Equation (5) which is given in Equation (28):

$$\begin{aligned}
 x_{11} + x_{13} &\leq 11 \\
 x_{22} + x_{24} + x_{25} + x_{26} &\leq 14
 \end{aligned}
 \tag{28}$$

The existing building is incomplete and needs more components to be complete. Figure 9 shows the left area in the second layer of the previous building.

Table 8 lists the left area (Span of 1-4 aux B) requirements in Layer 2: skin subsystem.

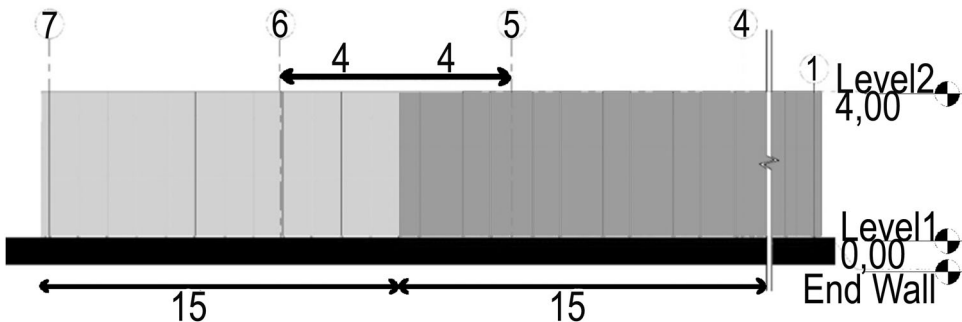
The allocation according to new requirements in the façade system is described in the equation. The length was considered in the objective function definition to maximize usage.

$$F(\text{cladding}) = \sum_{i=1}^2 C_{i1}x_{i1} = u_{11}l_{11}x_{11}
 \tag{29}$$

Decision variables of the required cladding panels are denoted by  $x_{ij}$ ;  $l_{ij}$  is the length of the allocated claddings, and  $u_{ij}$  is the feasibility of cladding allocation due to component properties. The total number of entries in every column demand must be equal or smaller to the number  $n_j$  of on hand elements in the chosen supplier. The supply constraint could be satisfied using Equation (5) which is given in Equation (30):

$$x_{11} \leq 11
 \tag{30}$$

Studies have shown that making circular design requires a ‘systems approach’. A systematic relationship governs different subsystems in a building. The internal interaction between the structure layer and skin layer could be controlled by their shared properties which is length. The façade system is designed to take the overall structure length into account. According to design variants, there are two different overall lengths in the span of 7-4 in aux A (take Figure 3 Into mind). It could be considered a constraint in problem definition. The system approach constraint could be



**Figure 5.** Western façade, Span4-7 aux A.

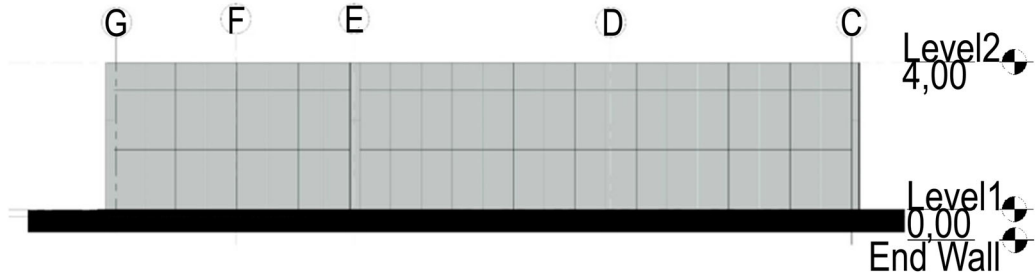


Figure 6. Northern façade, Span AC aux7.

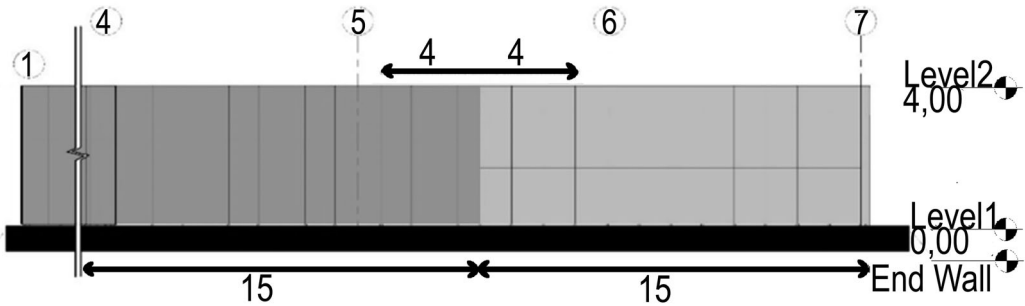


Figure 7. Eastern façade, Span 4-7 aux C.

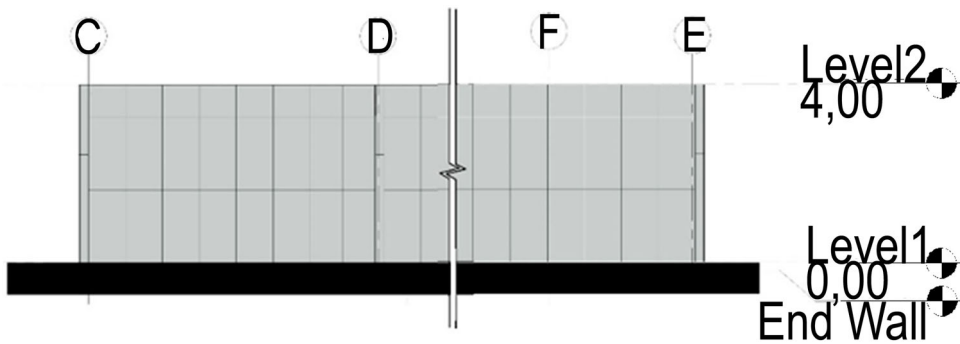


Figure 8. Southern façade, Span AB aux4.

satisfied using Equation (6) which is given in Equation (31) and Equation (32):

$$(u_{11}l_{11}x_{11} + u_{22}l_{22}x_{22}) \leq 28*(w_1 + w_2) + 30*w_3 \tag{31}$$

Span 7-4 in aux C is the same as above:

$$(u_{13}l_{13}x_{13} + u_{24}l_{24}x_{24}) \leq 28*(w_1 + w_2) + 30*w_3 \tag{32}$$

Decision variables of needed components are denoted by  $x_{ij}$ ;  $l_{ij}$  is the length of allocated

Table 8. Facade system requirements of the left area Span 1-4 aux D.

New requirements	Span	Overall length	Dimensions (length * height)	Suitable stock
1	Span 1-4 Aux B	21	3*4	Type1*7

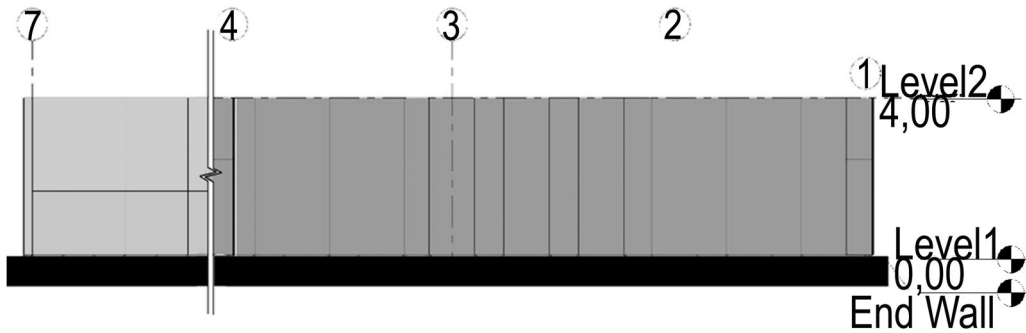


Figure 9. Western façade, Span 1–4 aux B.

components, and  $u_{ij}$  is the feasibility of components allocation according to their properties. Decision variables of the variants' structural design are denoted by  $\omega_j$ .

### Results and discussion

The issue is considered mathematical programming. Allocation of reclaimed building materials is the objective function. The decision variables are the required components. Accessible components and controlling changes in different layers are associated constraints.

Figure 10. shows optimization run applying a GENETIC solver provided by MATLAB software and results are noted in Table 9.

A feasible solution that maximizes the objective function is the optimal solution because the goal aims to maximize the reusing of reclaimed building materials in a Means-oriented design approach. Optimization Results show 245 as the optimum answer.

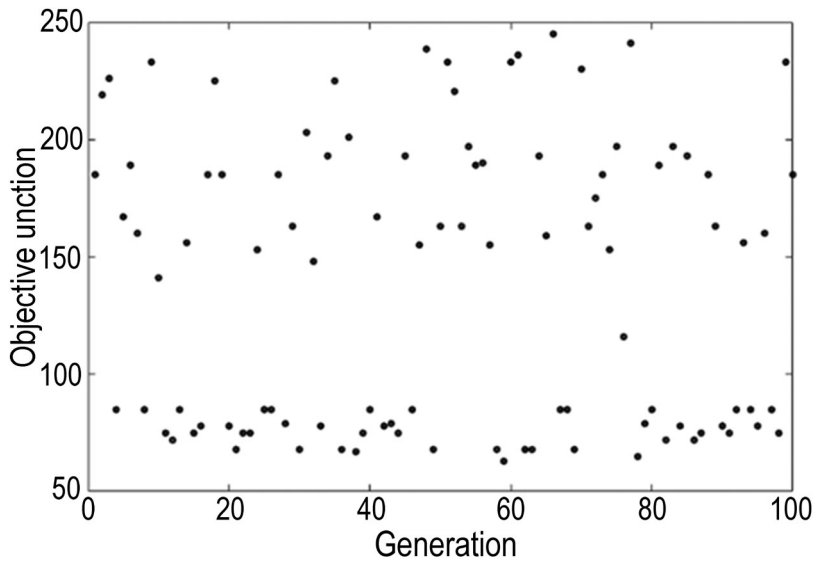
The decision variables in the maximum value of the objective function are noted in Figure 11.

As indicated in Figure 11,  $x_{55} = 1$ ,  $x_{56} = 0$ , and  $x_{57} = 0$ , which are  $w_1, w_2, w_3$ , respectively. The objective function is defined at the aim of maximizing the reuse of reclaimed building materials. Decision variables of needed beams are denoted by  $x_{ij}$ ,  $u_{ij}$  is the feasibility of beam allocation due to component properties. Three design variants according to design flexibility are defined. Decision variables of allocation variants are denoted by  $w_{ij}$ . The optimum allocation of available components on site aims to maximize reusing reclaimed building materials is the first option. The optimum design among design variants is determined by the optimum allocation of components.

Many approaches have been introduced to facilitate circular economy in the built environment. Various strategies are proposed to maintain product integrity as long as possible over multiple life-cycles and various guidelines are developed to help designers decide while they are designing the components. Although many frameworks and strategies are proposed to reclaim components, a method to facilitate the design process is still lacking. The design is complex because it evolves from available components. The design is adjusted according to size, predefined properties, and number of available stocks. The proposed method eases the complexity associated with design adjustment. To be more specific, there are design variants according to design flexibility; therefore, there are design allocation variants. The optimum allocation variant uses the most components among allocation variants. It determines the optimum component allocation that defines the evolved design.

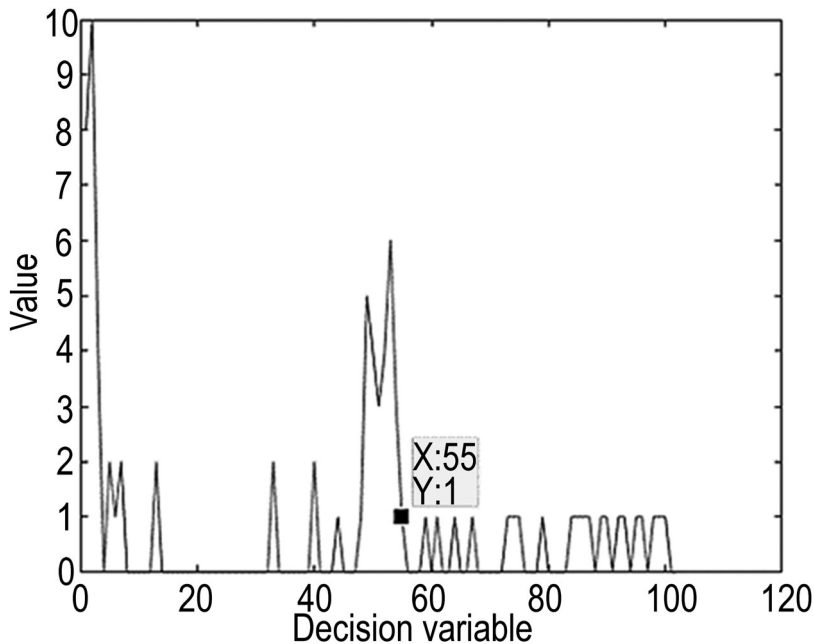
Table 9. Statistical analysis of the objective function values.

CV	Variance	Median	Mean	Minimum	Maximum
60.43189	3652.013	153	137.11	63	245

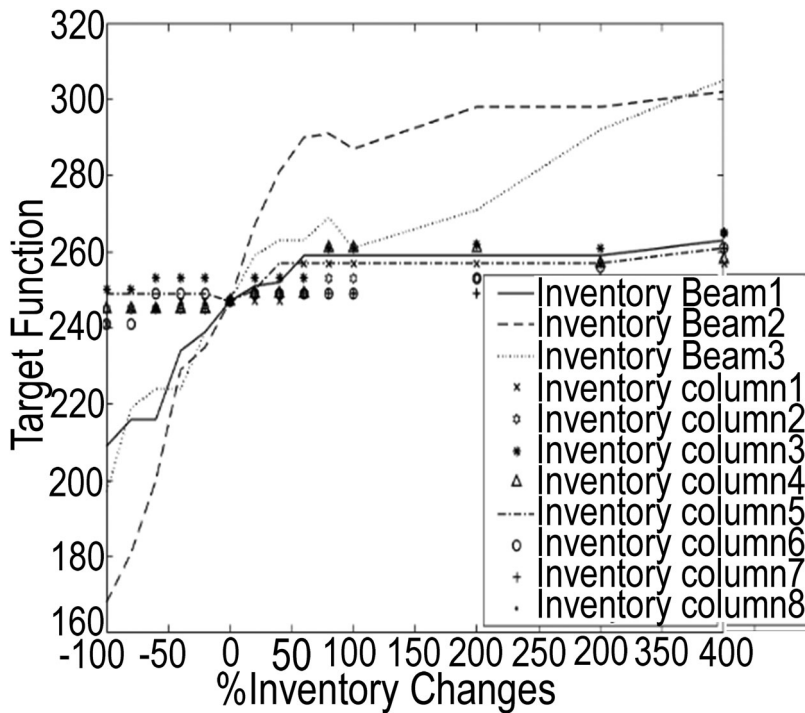


**Figure 10.** Optimization results show 245 as the optimum answer.

The circular economy reverses the design process. The design evolves from available components. The architect should take into consideration factors such as size, predefined properties, and the availability of stocks. The designer, who is focused on Means-oriented design, needs to address complexity, flexibility, experimentation, and adjustment throughout the design process. The proposed method eases the complexity associated with the design adjustment process for an architect. Moreover, it strives toward local self-sufficiency. If a company chooses to adopt a Circular Economy approach, which prioritizes product durability and reparability, it would need to reorganize



**Figure 11.** The decision variables value is allocated in the maximum value of the objective function.



**Figure 12.** Sensitivity analysis. The length of components is a changeable variable.

its supply chain and redesign its business model in order to create value. The proposed procedure would be advantageous for the product owner, as it enhances procurement efficiency by maximizing the utilization of available components. Also, local material usage is an important factor in efficient reuse. Reuse encompasses all aspects of environmental impact throughout the building's life cycle, with a specific focus on energy efficiency in transportation and material processing. The procedure outlined minimizes energy consumption by reducing transportation needs.

The sensitivity analysis noted in Figure 12, shows a correlation between the target function and the length of the components. The allocation process prioritize taller components,

The length is considered in the formulation definition as a parameter to determine the maximum length which is reused of available components. The sensitivity analysis indicated that formulation definition has an impact on the final result as this property was considered in the objective function definition. Measures should be taken to have a more independent result.

## Conclusion

The buildings' Environmental impact causes a reconsideration of conventional methods. The circular economy as a reaction to environmental pollution maintain product integrity as long as possible over multiple lifecycles through circular economy strategies (VRPs). Although various strategies are developed to facilitate VRPs, a strategy aimed at facilitating the design process from reclaimed components is still lacking. The design evolves from available components; so, it makes the design process complex.

A hypothetical example was proposed to demonstrate a design based on a system approach that underwent changes. The system approach involves dividing the building into layers and components that interact with each other. The objective was to maximize the reuse of available resources through an optimization problem. The components were defined using mathematical

programming. The first layer, which consists of structural elements such as beams and columns, was described in an equation. The second layer, known as the skin subsystem, was described in another equation and includes claddings. Specific constraints were defined to regulate the conformity of Layer 1 (structure) and Layer 2 (skin). Resource allocation Available components. The optimization results determined the optimal design allocation, which corresponded to the most efficient design.

The findings proved the adjustment process could be facilitated using mathematical programming as a resource manager considering a system approach in a building. Mathematical programming as a management science deals with the optimum allocation of limited resources in a competitive environment with associated constraints. The system approach divides the building into layers and components which interact. Mathematical programming provides the opportunity for defining a building through the component allocation. The objective function is the allocation of reclaimed building materials and the decision variables are the needed components. Mathematical programming permits defining constraints associated with a situation. Specific constraints define available components. We resort to the system approach, which states building components interplay with other system layers, to control the design changes. Specific constraints are defined to control the compatibility of the structure with the facade system. There are design variants according to flexibility in design; consequently, there are component allocation variants. Defining certain constraints permits to narrowing them to one component allocation. Each resource allocation variant defines a specific design, the optimal design is the one that reuse the available component the most. The optimization result determines the best possible allocation of scarce resources under the conditions of the project. Therefore, the process cut the adjustment design complexity.

This study is limited by the absence of a reliable source of information. The procurement process affects reuse efficiency and project objectives in terms of transportation and cost respectively. The need assessment determines the efficient identification of project needs. The efficient identification of project needs affect optimum allocation. Therefore, the need assessment affects the optimum design. There is no established reuse market and there is no reliable source of information about matters associated with suppliers. So, the scope of paper is narrow down to reuse maximal length.

More research is required in this area. The sensitivity analysis determines the presented method to define optimized design is subjected to length. It prioritizes the allocation of taller components, because length was considered in the objective function definition. So other parameters like the number of components should be considered simultaneously in formula definition to alleviate the mentioned effect and have a more objective result. Moreover, the prevailing viewpoint in this article was architectural. Structural viewpoint should be considered in structural component allocation to attain structural efficiency. The length was considered in the objective function definition to define the maximum length that is reused for the available component. Other efficient parameters such as embodied carbon and life cycle assessment could also be scrutinized, considering in the objective function.

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## Disclosure statement

No potential conflict of interest was reported by the author(s).

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