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Research paper

Algorithmically aided management of structure modularity at the design and execution stage

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The first author's name was misspelled in the original PDF version of this article, published on December 31, 2021. This has been corrected in the PDF version of the article on January 24, 2022. The other elements of the article remain unchanged.

Abstract: The interest in prefabricated building modules is constantly growing due to the increasing possibilities of analysing extensive data sets in computers and the popularity of BIM technology. The ability to manage the position, size and properties of many different elements make it easy to create and evaluate complete modular models at the design stage. Benefits of prefabrication include, among the others, decreased cost, minimisation of environmental impact, and reduced labour on-site. However, making structures and buildings suitable for prefabrication puts additional responsibility on the designer, who needs to choose the modular system, partition the structure and prepare detailed schedules. The article refers to digital control over modular design in the context of the increasing complexity of structures. It focuses on methods and tools that either reduce the designer's labour or provide him with information that can be used to optimise the structure in terms of efficiency or cost. The article organises the existing trends and presents three experiments on algorithmic control of modular structures to outline the differences in computational methods suitable for particular technologies: masonry, steel, glass and timber construction. The research illustrated in the article was undertaken in response to the need to develop construction technologies in line with the sustainable development trend.

Keywords: modularity, prefabrication, tessellation, tiling, optimization, management

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1. Introduction

1.1. Research problem and scope

The paper discusses the influence of contemporary computational methods on the design of modular, tectonic structures. The analysis of presented proprietary projects, along with related works of other researchers, aims to prove that new technological possibilities of managing large and complex data sets may impact efficiency and expression of the designs and be a root of a new rational style. We compare algorithms applied to designs of structures of different natures to outline a typology of automation methods useful for a designer who plans a design strategy. All of the presented digital design methods were intended to aid low-tech, practical processes to reflect the building standards of a developing country [1]. We refer to the traditional bricklaying, carpentry, and simple steel structure assemblies.

First, we outline modular design's historical background and tendencies, emphasizing how technological and scientific development impacted the design profession. The chapter ends with remarks on the computational era. The following section is dedicated to a detailed case study where three design cases are presented along with algorithms used in the process. The algorithms are presented as flowcharts and critically evaluated. Finally, we gather the observations and compare them with the findings of other researchers. The paper concludes with a justification of further research on algorithmic management of modular structures at the design stage.

1.2. Historical development

The use of modular tectonic structures is rooted in the history of construction and the theory of architecture. Building from repetitive particles of material was initially purely practical. The size of the stone blocks, wooden beams, and bricks was adapted to the transport possibilities, the techniques of erecting buildings with the strength of human muscles, and the simplest machines' characteristics. In Vitruvius' treatise, we find a whole catalogue of justifications for the modularization of a building structure. It begins with an anthropological reason: according to the author, the methods of combining small elements into a whole were observed by man in the works of nature and then improved through multiple trials and errors [2]. Vitruvius writes that thanks to the modularity and the proper pattern of the joints, the brick structure "gains strength and is (...) pleasing to the eye" [2].

The theoretical discourse of the Renaissance uses ancient findings to describe aggregation techniques. Alberti [3] mentions the necessity to run stone and brick threads "along designated lines and (...) angles". Renaissance buildings arising from a fascination with perspective and, more broadly, with the theory of perception, use modularity to emphasize spatial impressions.

The architecture of later centuries was focused on the visual perception of building elements. Decoration obscured the structural modularity. Changes in valuation were finally introduced in the nineteenth century. Eugène Viollet-le-Duc drew attention to the beauty of medieval buildings that displayed the structural sense of individual elements and their aggregation [4]. John Ruskin [5], opening the way for the discourse of modern architecture, used an ethical evaluation to assess the achievements of earlier epochs. The tectonic expression of the building, its structural modularity was called here the truth, as opposed to false, superficial decorations.

In comparison to the previous epochs, modernism appears as a renaissance of interest in structure modularity. We see it in the widespread use of unplastered walls, in the execution of bindings, in the creation of innovative prefabricated elements based on utilitarian premises.

Contemporary aggregations add a component of the information era to the historical ideas – the digital medium capable of automation, variability, and transcoding influences the flexibility of aggregations. Designers can easily create representations of various portions of building material and test their performance in the final structure. The ease of combining modules of different sizes allows for creation of highly complex aggregation systems, which modernists were striving for, with minimal executive possibilities [6]. Even the traditional building block, a brick, becomes the subject of the most innovative experiments. The realisations of Gramazio and Kohler [7] indicate a tendency in the evolution of aggregated structures, resulting in the creation of a new canon of efficiency and new aesthetic systems.

1.3. Research methodology

The paper presents a comparison of three design cases with different structural conditions. The broad comparison allowed to emphasize methodological differences. A common feature of the studies is an attempt to answer the questions posed in the traditional architectural discourse:

1. Can a given form be built using a specific set of elements? If not, how should it be adjusted?
2. How to organize the construction and delivery site to make the building process the most effective and least problematic for the construction team?
3. Can a utilitarian building system based on repeatable elements and their configurations be a premise of an aesthetic system?

We supplemented these historically grounded dilemmas with questions posed by digital design methodologies:

1. Does computer control over building plan discretization affect the qualitative and quantitative parameters of the build process?
2. Do the automated digital design methods affect the way modular systems are developed?
3. Does the digital control over the construction site influence the aggregation paradigm: how much the module, rather than the building form, has become the subject of design?

2. Case study

We present three cases of using proprietary computer programs to support the design of modular forms. We implemented the following algorithms in the C# language and tested them in Rhinoceros/Grasshopper CAD environment.

2.1. Modular masonry

2.1.1. Program description

The first described case regards a building made of prefabricated blocks. The task was to arrange the blocks in a single-family house floor plan, assuming that the blocks cannot be cut at the construction site. In such cases, the designer must adjust the plan to fit in the defined modular grid. We propose an automated way of performing this adjustment while letting the designer choose which option is the best, given significant geometric analyses and material schedules. We prepared a parametric model which contains proprietary non-linear algorithms.

The parametric model requires basic geometric data as an input (Fig. 1). The adjustment of walls to a building module is performed on a modular grid. The program snaps the wall axes to the nearest grid axis. As a result, all wall axes have a length that is a multiple of half the module.

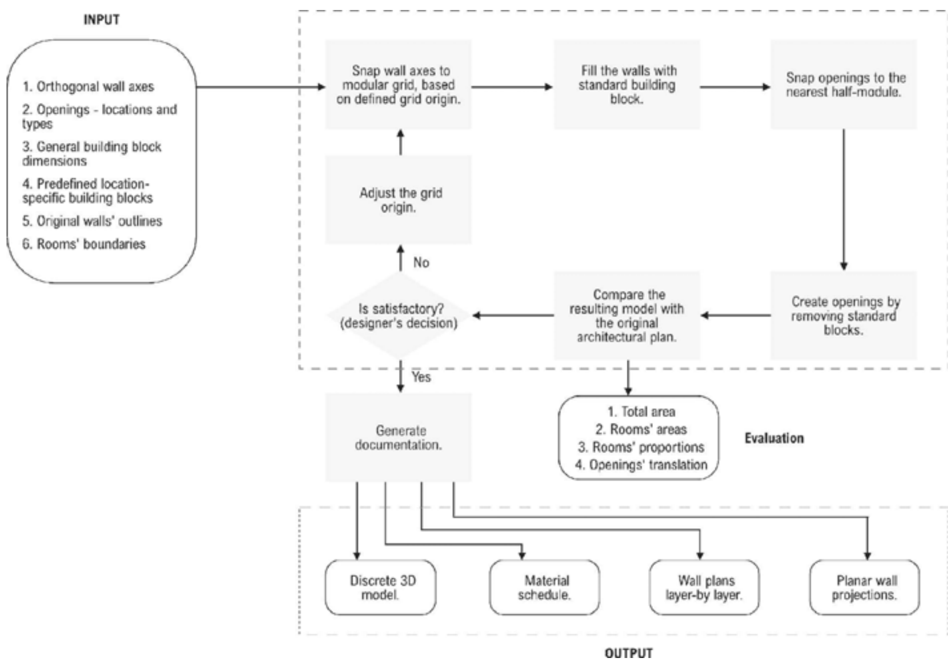

Fig. 1. Algorithm flow-chart

The adjusted axes serve as baselines for 3D building blocks. The program joins the axis segments into a graph and processes its edges consecutively, starting from a node with the smallest valence. The blocks are arranged in an alternating manner, according to the producer's guidelines. After this step, the openings are introduced in the model. The user-specified locations are snapped to the nearest wall and adjusted to fit precisely in the modular grid. Standard blocks are removed from the opening and, where necessary, replaced with special blocks (lintel or half-modules) (Fig. 2).

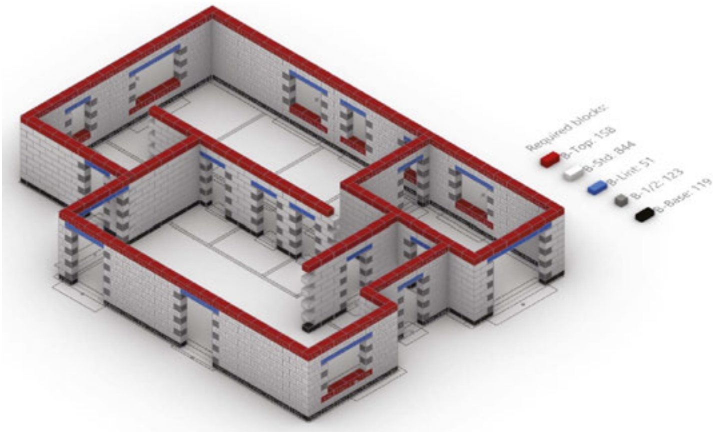

Fig. 2. Exemplary program output

The prepared modular 3D model is then analysed and evaluated. The evaluation process starts by outlining the new room boundaries. They are compared with the original rooms in

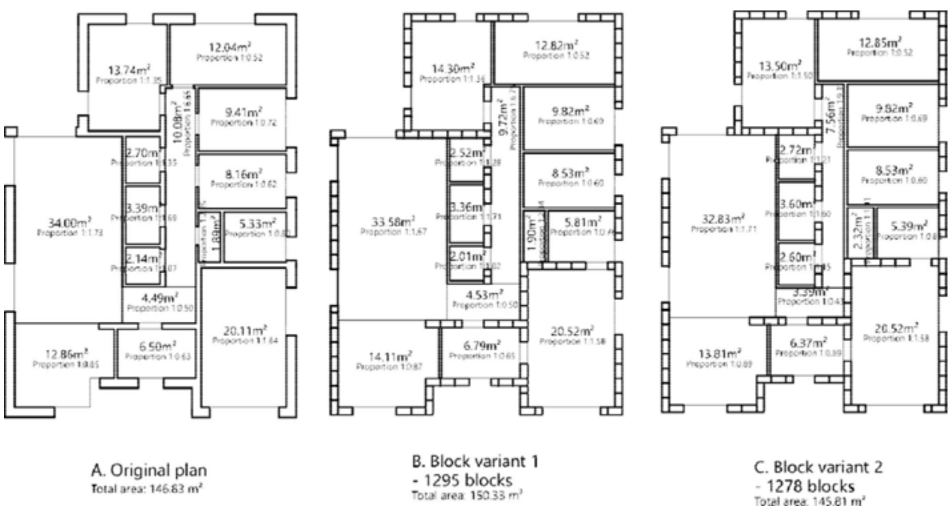

Fig. 3. Alternative versions of the same floor plan, program output

terms of proportions and area. The designer can decide if the produced model is satisfactory. If not, the modular grid origin can be changed to produce a different wall axis adjustment.

2.1.2. Results

We tested the program by processing typical single-family house floor plans (Fig. 3). We noted a few issues that should be addressed in the future. The axes that are adjusted to the building module sometimes result in an invalid floor plan. For instance, an area designed as a corridor becomes too narrow in terms of building code. In some cases, openings stop fitting in the walls. There is a finite number of possible adjustments, but currently, our tool does not identify them automatically. An additional solver could be introduced to automatically find the best adjustment according to the designer's intent.

2.2. Tunnel covered with solar panels

2.2.1. Program description

The second application of digital tools in designing modular structures concerns installing solar panels on a tunnel running over a curved bicycle path. The structure is made from identical prefabricated elements. Automating the modelling process aims to ease the assessment of placing such tunnels in different geographic locations by decreasing the time needed to prepare part schedules and analyse the solar panels' efficiency.

The panels are flat and rectangular, and the tunnel's surface is doubly curved if the path is not straight. In addition, the panels can be rotated by the designer to create different visual patterns and increase the aesthetic value of the structure. Those conditions create difficulties for the designer and make it time-consuming to cover the path manually.

We prepared a computer program that, based on the route and input parameters, arranges the main elements of the structure, generates a pattern for the arrangement of panels, analyses potential collisions, and creates schedules. The primary tunnel structure consists of uniform circular frames with a constant radius. Straight steel tubes run between the frames, forming a second-row structure to which the photovoltaic panels are attached directly from above (Fig. 4).

We prepared two different versions of the tesselation algorithm and compared the results they give. They both share methods that generate the primary structure and panels' pattern on a plane (Fig. 5). In this article, we focus only on the distribution of the panels on the top surface.

The first distribution method is based on a parametric division of the top surface created over the tunnel (Fig. 6). First, the program finds the shortest longitudinal isocurve of this surface. This curve, unrolled, represents the maximal span that can be used for placing the panels. Its length determines how many divisions of the surface will be created. The surface is then parametrically divided into tiles. The tiles are used to position the panels, which are further rotated. Program analyses collisions after modelling and, if any collision occurs, decreases the number of longitudinal divisions.

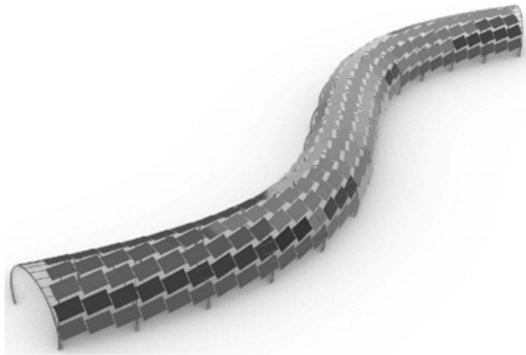

Fig. 4. Program output, 3D model with primary and secondary structures covered with rotated panels

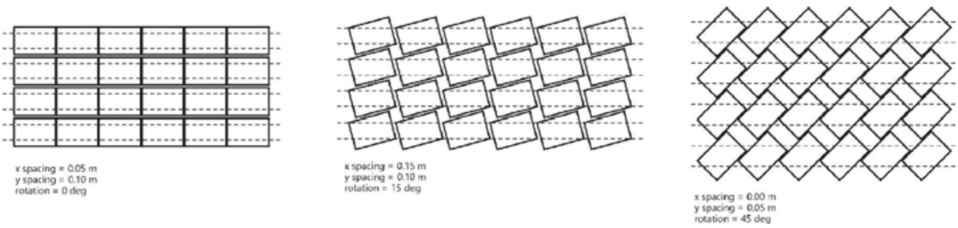

Fig. 5. Examples of possible panel patterns generated on a plane

The second distribution method is based on analysing the secondary tunnel structure (the purlins) to calculate how many panels can be attached (Fig. 7). Similarly to the first method, the shortest chain of purlins is identified in the model. An equidistant division is performed on this chain, where the distance between consecutive points is equal to the distance between the centres of panels generated on a plane. This process allows calculating how many panels can be created along the tunnel.

2.2.2. Results

We used both methods to model tunnels over paths that had one or two turns. The results presented here concern the former case (Fig. 8). We noticed that the second algorithm performs better, distributing more panels on the same tunnel and maintaining a more regular pattern. We performed an analysis of the distribution of the rows by unrolling the surfaces that they create. The surface stripes produced by the second method fit better on the doubly curved top surface. The results indicate that the second method is more suitable for further development.

The current development stage does not include the calculation of the energy produced by the panels. Only their number is evaluated. In the future, adding such functionality based on the geographic location could improve the program's usefulness in quickly performing project feasibility studies.

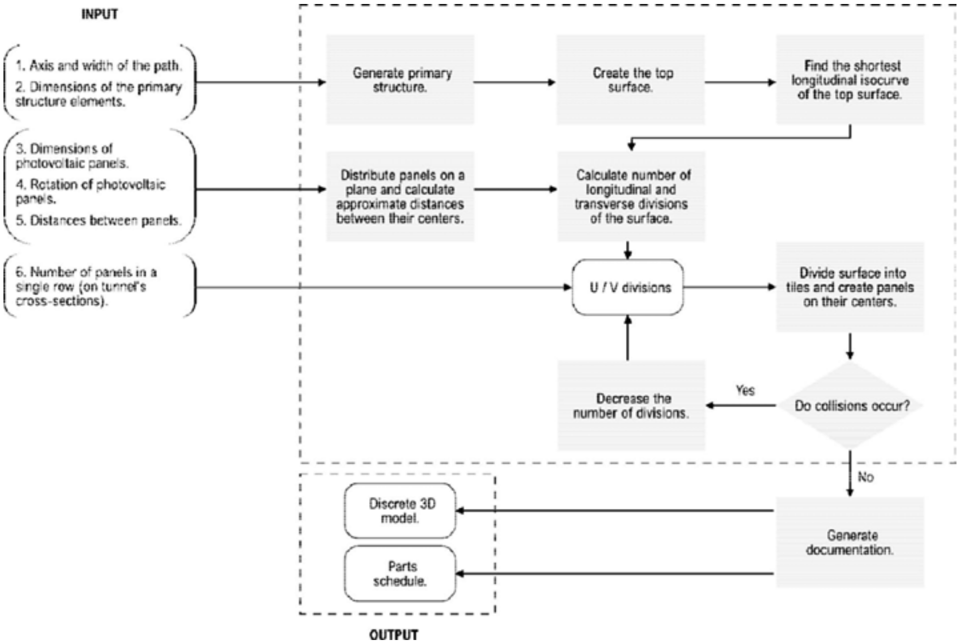

Fig. 6. Flow-chart of the panel distribution algorithm, first version

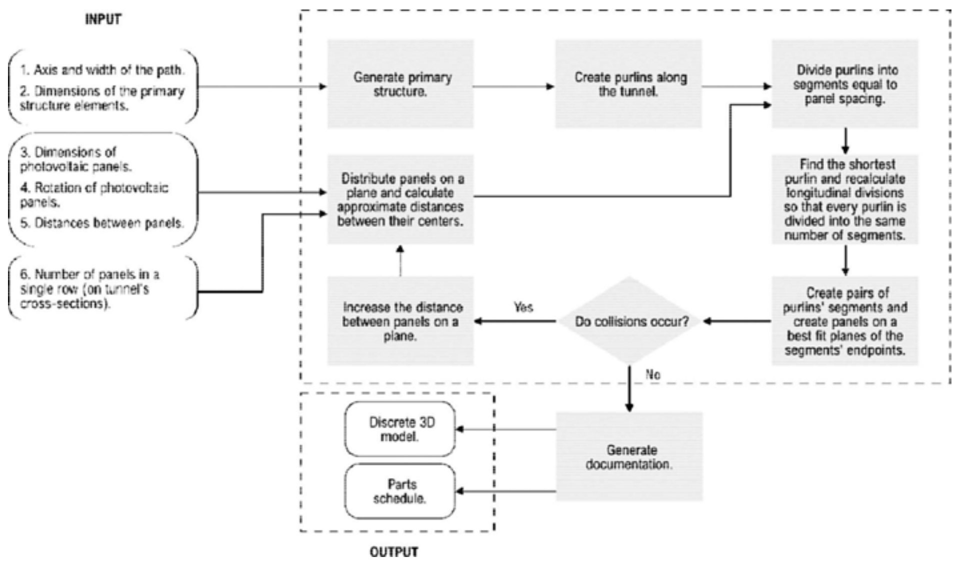

Fig. 7. Flow-chart of the panel distribution algorithm, second version

2.3. Timber façade cladding

2.3.1. Program description

The third studied problem relates to optimising the division of the façade planks concerning the available stock material. In essence, it is a problem of one-dimensional nesting and generating cut schedules that minimise material loss. However, we added an optimisation goal related to the carpenters' behaviour on a construction site. The supplier provides stock planks of specific lengths, and the carpenters must cut them to desired lengths. The most optimal material use often requires using the same stock plank to make façade planks in very different parts of the façade, sometimes on a different wall (Fig. 9). A large spread of planks produces from the same stock plank increases the amount of work that the carpenters must spend on managing the material, numbering the leftover parts, and thinking of the arrangement. Such a situation increases the mental effort of the contractor's team. To minimise it, we programmed an optimisation algorithm that balances between minimising the material loss and simplifying the carpenters' work.

We implemented two algorithms to solve the problems mentioned above. One simulates the casual carpenter's behaviour (Fig. 10), and we use it to produce control samples. The other optimises material cost while maintaining a small spread of planks made by cutting a single stock plank (Fig. 11).

The input data for both programs consist of:

1. Two-dimensional plans of the façades with cladding represented as closed polylines.
2. Set of lengths of available stock planks and their prices.

The first set of procedures is mutual for both versions. The program analyses provided cladding plans, sorts the planks by X coordinate of their centre points, and saves the data in memory.

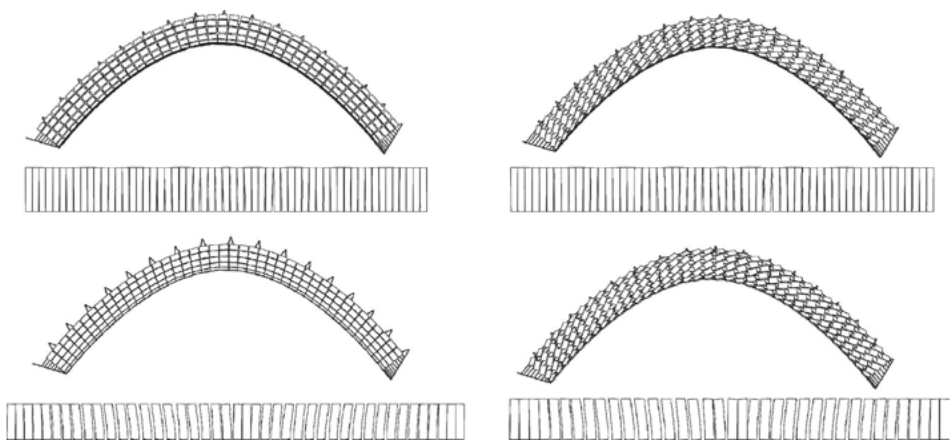

Fig. 8. Program output and unrolled panel rows. Top plots were produced with the first version of the algorithm, bottom with the second. The left column shows straight panels, right column panels rotated by 15 degrees. Number of panels: top-left = 240, bottom-left = 258, top-right = 204, bottom-right = 222

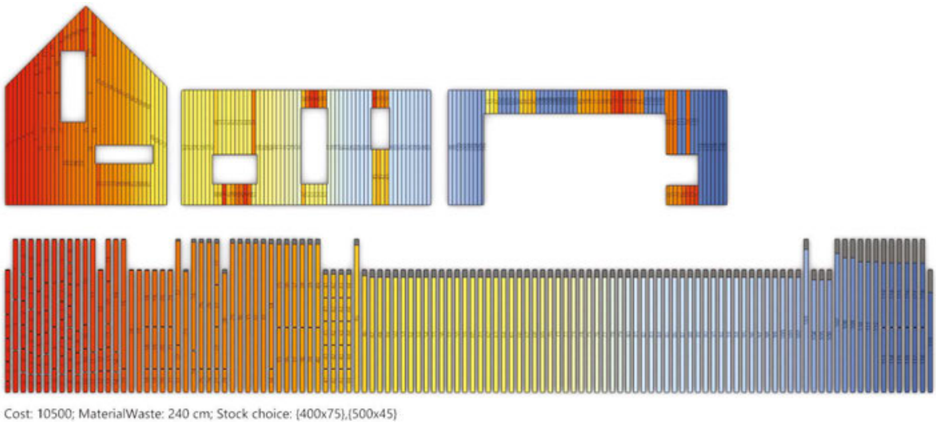

Fig. 9. Exemplary program output. Top: façade plans with cladding. Bottom: stock material required to make the cladding. The source stock planks are numbered and colour coded

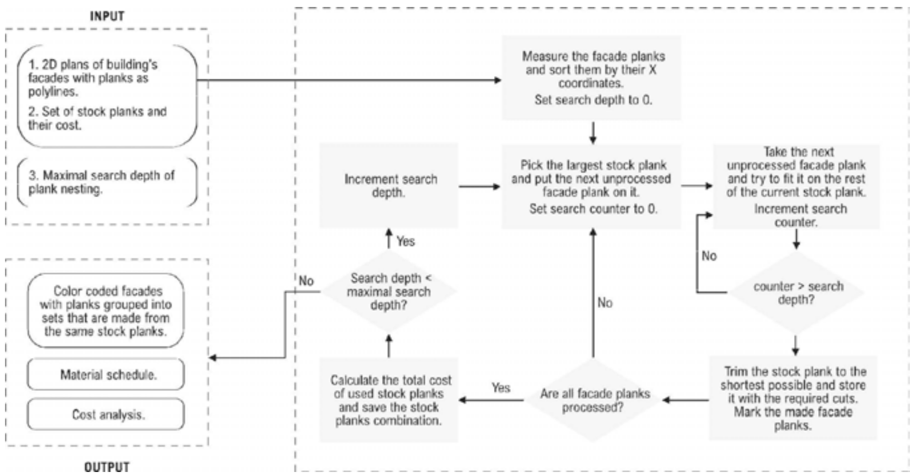

Fig. 10. "Carpenter simulation" algorithm

The program that simulates the carpenter behaviour starts the planning by taking the longest stock plank and producing the first façade plank from the collection. The leftover material is then checked against several following façade planks to determine if it can be used again. The user sets the number of tested planks. After checking all possibilities, the rest of the material is discarded. The actions are repeated with new stock planks after all façade planks are processed.

The other program first creates all possible combinations of cuts of the stock planks that produce a complete set of planks required for cladding. Such combinations are then sorted by the material waste, ascending, which means the most efficient is at the beginning of the list. The program enters a loop that ends when all facade planks are processed. Every

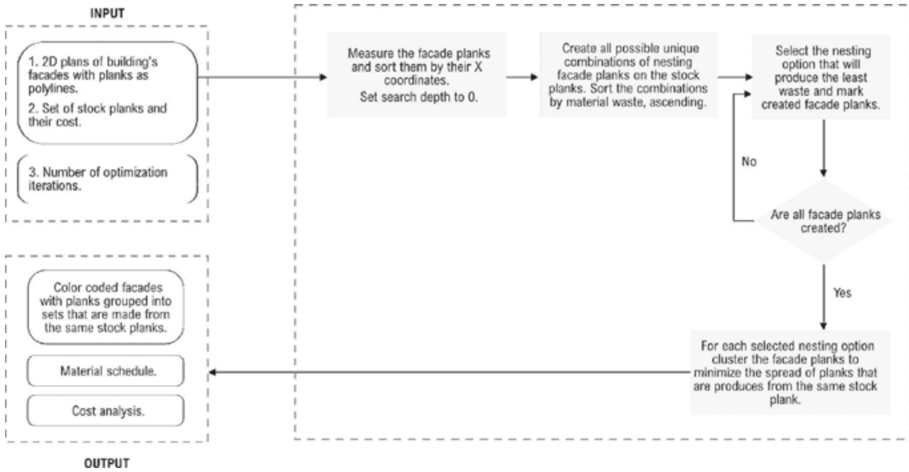

Fig. 11. Cost optimisation algorithm

iteration finds the most utilised stock plank cut combination and marks the facade planks produced with it. After processing all facade planks, the last program method numbers the used stock planks. It organises the produced facade planks to minimise the scattering of products of cutting the same stock element.

2.3.2. Results

Both versions of the algorithm generate a coloured schedule of material needed to clad the analysed facades. Planks on the facades are numbered and coloured accordingly, which allows seeing the distribution of products of cutting the stock planks. We tested the program on the designs of two houses with timber cladding. As we expected, the material cost was consistently lower for combinations produced by the second algorithm. However, the scattering of elements increased as well. The optimisation tool is effective at generating the most optimal cutting schedule for a given cladding. However, we assumed that the supplied planks would be free of imperfections (e.g. knots that make cutting impossible). We take the width of a saw blade into account when generating cuts, but an additional tolerance might be introduced to make up for possible faulty performance.

3. Discussion

When assessing the research cases presented in the article, it should be noted that the issue of modularity of structures is not homogeneous. Due to different interpretations of the problem and different design conditions, the computational designer must look for distinct methods. In the context of digital tools, this means developing a different algorithm and formulating problem-specific optimisation criteria. Below we present conclusions related to the three cases, which we based on analyses of the programs' outputs and comparisons with the results of other researchers.

3.1. Automated masonry planning

Our algorithm serves as a quick scheduling tool for the architect while informing him about the changes required to adjust the nominal plan to a given modular system. The designer instantly sees the block distribution, receives the material schedule, and can analyse differences between the original and modular plans. To adjust to the local availability of advanced fabrication tools (CNC, robots, VR), we limited the scope of research to assembly automation. We relied on detailed instruction for the workmen to ease the building process. Similar approaches were taken in the areas where high construction technology is not available and manual labour is preferred [1]. Successful experiments prove robotic arms, popular among researchers of discrete assemblies, are not necessary to ease building complex structures out of bricks [8]. Current trends in masonry planning show the focus is put on the robotic assembly of complex, non-orthogonal structures. Gramazio and Kohler research the robotic fabrication of brick walls that are freely positioned and rotated to achieve a particular appearance. The bricks are intended to be laid by robotic arms either on-site or prefabricated [9]. Some designers propose redesigning the bricks themselves, which should allow for easy assembly of curved surfaces predefined by the bricks' twisted shapes [10]. We believe the limitations in developing countries ask for low-tech solutions and design methods tailored to improve the efficiency of building casual structures rather than seeking ways of fabricating novel, complex forms. Our tools can improve a simple building process based on a dry assembly of orthogonal blocks but do not help design complex, expressive structures.

3.2. Doubly-curved surface tesselation

Both versions of the program allow for fast evaluation of the design in any given location. The program bridges a rigid building system that consists of identical parts with a free-form double-curved surface tesselation. The constraint of using identical parts results in a changed aesthetic appearance of the surface resulting from rational planning. There are approaches to tesselating a doubly-curved surface into rectangular patterns. For instance, Liapi and Papantoniou propose using projections and geometric approximations to generate tilted rectangular tiles on any surface [11]. However, they do not constrain the sizes of the tiles, allowing them to be different in the final solution. Some authors propose dividing the surface into stripes along asymptotic rather than principal curvature directions [12]. We intend to test such methods to possibly find a more efficient distribution of the panels or a different aesthetic expression. However, the tool we prepared is not intended for designing tight tesselations, requiring fabricating custom curved panels. That approach puts more focus on robotic fabrication methods and optimisation, which aims at reducing the number of panel "families" [13, 14]. We sought the closest approximation of a doubly-curved surface using only a single type of flat, rectangular element to utilise the potential of prefabrication and reduce the demand for highly qualified construction teams.

3.3. Wall cladding

The program decreases the time that the designer needs to spend on planning cladding fabrication. The tests we performed showed that manual planning takes around 8-12 working hours, while our program solves the same problem in less than a minute. In addition, it gives better results in terms of total cost and allows testing multiple alternatives. Quick generation of cut plans and material schedules can serve as a method to test the tesselation of a building's facade and be further used in a broader optimisation algorithm. Ostrowska-Wawryniuk presented a similar approach to minimising standardised material waste through adjusting the building module size to a specific design [15]. Our program allows for inputting different sets of standard material pieces, which might be used to compare offers of different suppliers. It also serves well as an evaluative tool in the process of façade tesselation. However, it is limited to analysing cladding with planks of the same width and cannot process timber sheets with sizes variable in both dimensions.

4. Conclusions

An architectural and construction project can be described as a complex fabrication, transport and assembly process. The use of modular portions of the material allowed figuring out and constructing the largest known structures of the technical civilisation. The size and form of these basic components significantly differ from the features of the final building. The building modules are subordinate to ergonomics, logistics and assembly requirements as well as design requirements.

The research presented in the article follows the historical path of rational, tectonic work on the architectural matter. The studied digital design methods do not express a desire to create a new style [16]. On the contrary, in line with the postulates of modernism, they serve the idea of a more efficient, faster and more accessible building process [17] by aiding in the conversion of the design plans into assemblies of a finite number of material portions along with assembly instructions. The authors intend to follow John Ruskin's idea: the solutions based on pragmatic premises create the final material and, as such, aesthetic character of the building.

Even though digitisation significantly changed the architectural practice, it could not have caused the departure from the aggregative nature of the building process. However, the assembly process and components have gained new functionalities. Since the project today consists of data expressed through a digital medium, both the manageable complexity and the flexibility of making changes had increased. On a general level, this means the designers can take algorithmic control over the configuration of the aggregation patterns and logistics. It can make the project more rational and facilitate the assembly through automation or detailed instructions. On a smaller scale, it is expressed most fully in the phenomenon of mass customisation that allows efficient production of sets of distinct elements.

The examples presented in the article illustrate the role of digital design methods development in changing the conditions of architectural practice. On the one hand, they respond to the need for high efficiency of the fabrication and assembly processes. On the other hand, they result in a new, rational architectural expression. According to the authors, they can contribute to the digital rationalism trend, ideologically consistent with the postulates of twentieth-century architecture, but achieved by different (digital) means and introducing new aesthetic results. These practical and philosophical issues justify the further explorations of algorithmic aid in managing the structures' modularity.

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Algorytmiczne wspomaganie zarządzania modularnością struktur na etapie projektowania i wykonawstwa

Słowa kluczowe: modularność, prefabrykacja, teselacja, optymalizacja, zarządzanie

Streszczenie:

Wykorzystanie modularnych struktur tektonicznych jest głęboko zakorzenione w historii realizacji budowlanej i w teorii architektury. Początkowo budowanie z powtarzalnych porcji materiału było wyłącznie skutkiem uwarunkowań praktycznych. Rozmiar bloków kamiennych, belek drewnianych i cegieł dostosowywano do możliwości transportowych, technik wznoszenia budowli siłą ludzkich mięśni i charakterystyki najprostszych maszyn.

Dyskurs teoretyczny renesansu rozszerza rozważania o modularności o aspekty estetyczne. Alberti wspomina o konieczności prowadzenia wątków kamiennych i ceglanych „według wyznaczonych linii i (. . .) kątów". Budowle nowożytne, wyrastające z fascynacji perspektywą i szerzej, teorią postrzegania, wykorzystują modularność dla uwypuklenia wrażeń przestrzennych.

Architektura wieków późniejszych skupiona była raczej na wizualnym odbiorze elementów budowlanych niż na ich tektonicznym uporządkowaniu. Dekoracja podporządkowana względom estetycznym przesłaniała wewnętrzne modularne struktury. Zmiany w wartościowaniu przyniósł dopiero wiek dziewiętnasty. Eugène Viollet-le-Duc zwrócił uwagę na piękno średniowiecznych budowli, które eksponowały strukturalny sens pojedynczych elementów i ich agregacji. John Ruskin, otwierając drogę dla dyskursu architektury nowoczesnej, zastosował dla oceny dorobku wcześniejszych epok wartościowania bliskie etycznemu. Tektoniczna struktura budowli jest przez niego nazwana prawdą w odróżnieniu od powierzchownej dekoracji.

Na tle powyższych rozważań modernizm jawi się jako renesans zainteresowania modularnością. Widzimy to w powszechnym wykorzystaniu nietynkowanych murów, w ekspozycji wiązań, w tworzeniu nowatorskich prefabrykowanych elementów.

Współczesne agregacje dodają do historycznych koncepcji komponent ery informacyjnej. Jest nim cyfrowe medium, które obecnie stanowi naturalny język reprezentacji projektów architektonicznych. W przeciwieństwie do medium analogowego składa się z części (bitów), co sprawia, że lepiej służy do opisu struktur modularnych. Dzięki rosnącej mocy obliczeniowej komputerów wzrastają możliwości zarządzania rozległymi zbiorami danych, co pozwala zapisywać w projekcie dokładne informacje o rodzaju, położeniu, kształcie i innych właściwościach części składowych.

Autorzy zestawiają eksperymenty dotyczące algorytmicznego wspomagania projektowania struktur modularnych o różnych naturach. Wykazują, że różne technologie wymagają zastosowania innych metod agregacji. Przedstawione są metody rozliczania prefabrykowanych bloczków w niedostosowanym planie architektonicznym, teselacje dwukrzywiznowych powierzchni za pomocą identycznych płaskich elementów oraz optymalizacja rozkładu desek elewacyjnych w kontekście określonych zasobów materiałowych.

Własne koncepcje algorytmów porównywane są z obecnymi trendami w dziedzinie badań nad komputerowym wspomaganiem projektowania. Współczesne wysiłki skupiają się na wykorzystaniu wysokiej technologii (wielkoskalowy druk 3D, programowalne ramiona robotyczne) do wykonywania złożonych struktur, które nie mogłyby powstać bez udziału komputera. Autorzy zauważają, że tego rodzaju poszukiwania nie mają zastosowania w praktyce w krajach rozwijających się, gdzie innowacje technologiczne nie są popularne, a ręczne wykonawstwo dominuje ze względów tradycyjnych i ekonomicznych. Uzasadniają tym skupienie się na uproszczeniu projektowania zamiast na zwiększaniu poziomu złożoności, a zautomatyzowane procesy budowy zastępują łatwo dostępnymi i zrozumiałymi instrukcjami dla wykonawców. Autorzy dostrzegają przestrzeń do dalszych badań w zakresie algorytmicznego wspomagania projektowania struktur tradycyjnych, nieskomplikowanych technologicznie, w przeciwieństwie do wykorzystywania potencjału obliczeniowego komputera do tworzenia nowych form.

Przedstawione w artykule przykłady ilustrują rolę rozwoju cyfrowych metod projektowania w transformacji uwarunkowań praktyki architektonicznej. Z jednej strony odpowiadają na potrzebę wysokiej wydajności procesów wytwarzania, transportu i montażu. Z drugiej strony efektem ich zastosowania jest nowy, racjonalny i oszczędny wyraz architektoniczny. Według autorów mogą one wnieść wkład w nurt racjonalizmu cyfrowego, ideologicznie spójnego z postulatami architektury XX wieku, ale osiąganego innymi (cyfrowymi) środkami i wprowadzającego nowe efekty estetyczne. Te praktyczne i filozoficzne kwestie uzasadniają dalsze poszukiwania algorytmicznej pomocy w zarządzaniu modułowością struktur.

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