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Formal and technological aspects of additively manufactured architecture in the light of geometric parameters of selected objects

Formalne i technologiczne aspekty architektury wytwarzanej addytywnie w świetle parametrów geometrycznych wybranych obiektów

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Abstract. The article presents the results of analyses of the hitherto unexplored relationship between an artifact and its manufacturing tool in architecture and additive methods (AM). The purpose of the study was to identify and interpret these relationships. For this purpose, the authors examined the characteristics of selected 82 realizations created between 2004 and 2021. In the research, two author's indicators were introduced: scale (WS) and detail (WD). The analyses conducted indicate a close relationship between design methods and manufacturing technology.
Keywords: architectural design; additive manufacturing; tool-artefact relationship; geometrical parameters of design and technology.

Streszczenie. Artykuł prezentuje wyniki analiz niezbadanej dotychczas relacji między artefaktem a narzędziem jego wytwarzania w obszarze architektury i metod addytywnych (AM). Celem pracy była identyfikacja i interpretacja tych zależności. Dokonano tego, badając charakterystyki wybranych 82 realizacji powstałych w latach 2004 – 2021. W tym celu wprowadzono dwa autorskie wskaźniki: skali (WS) oraz detalu (WD). Przeprowadzone analizy wskazują na ścisłe powiązanie metod projektowych z technologią wytwarzania.
Słowa kluczowe: projektowanie architektoniczne; wytwarzanie addytywne; relacja narzędzie-artefakt; geometryczne parametry projektowe i technologiczne.

The presented study aimed to systematize knowledge on the relationship between architectural objects' characteristics and their fabrication methods, namely additive manufacturing (AM). The analysis was conducted through the lens of measurable technological and architectural parameters describing objects created using AM. Additionally, the objective was to recognize and interpret the relationships between these parameters against the backdrop of the design – production tool dependencies in architecture.

Architectural Idea and Its Realization in Context of Objects' Measurable Parameters

Architecture is an art inherently linked to materiality. This materiality can be understood on various levels and through multiple aspects, ranging from perceiving architecture as a physical artifact, the role of materials as a building substance, or the issues related to tools used to shape materials and erect buildings.

The complex nature of architectural works necessitates both qualitative and quantitative research into constructed buildings. Architecture can be perceived as a manifestation of function, an expression of ideas, an attribute of power, or reduced to an aesthetic object. Such interpretations made within a qualitative approach dominate the analysis of creative aspects of architecture. In contrast, the building construction process focuses on a quantitative approach, emphasizing what is measurable. This approach has always been present, partly due to the costliness of the investment process, which requires rationalization through quantification to determine expenditures – materials, labor, and tools. Can the dominant qualitative approach in historical and critical analyses of architecture be supplemented with quantifying architectural activities, primarily those linked to the construction of objects, i.e., material and tool-related aspects? To what extent can measurable aspects of an architectural work, understood as an artifact, provide essential information about its construction process and, furthermore, its design? The authors attempt to find answers to these questions throughout the article.

Qualitative analysis of buildings as works of architecture often focuses on their phenomenological aesthetic interpretations – such as in the case of Roman Ingarden [1]

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– rarely referring to measurable genetic characteristics, especially how materials, techniques, and tools used influenced the form. Materiality in the qualitative approach is significant only to the extent it directly manifests in a building's form. The significance of the material is thus reduced to its sensual perception, the impressions it evokes, constituting the work's existential basis. Such an approach, treating architecture as "pure art" justified on aesthetic grounds, has and continues to result in purely formal generalizations, serving as, for example, the basis for periodizing architectural history based on stylistic features. This article presents a different approach linking characteristics of an artifact (a building or its parts) with the tool used, thus the physical process of object formation.

The earliest surviving architectural drawings, seemingly referring to the notation of an idea enabling its embodiment as a building, are actually contract illustrations, indicating quantitative architectural features associated with the construction process [2]. Architectural drawings – somewhat substituting for buildings – are often also the basis for quantitative analysis, mainly referring to the building's geometry, somewhat detached from the manufacturing process and material. These analyses focus on proportions and mathematical relationships between elements, as seen in medieval traceries [3] or Baroque buildings [4]. Material and tool aspects are decidedly marginal here; the focus is on the form itself and its ideological connotations [5]. Against this backdrop, an interesting case of linking formal notation – geometric analysis – with the manufacturing process is the art of stereotomy. A widespread French method in the 16th and 17th centuries of creating drawings tracing complex geometric parts of a building, such as vaults or spiral stairs, allowed to carve these out of stone by a skilled craftsman – stonemason. They precisely transferred shapes and dimensions onto a material, which was then processed so that parts, limited in size by the dimensions of stone blocks, fit together during building erection [6]. Analyses of these drawings provide interesting information sources on contemporary geometric knowledge and, particularly valuable, on the building practice of the Mannerist and Baroque periods. It also exemplifies the influence of the materiality of the building construction process on design, manifested in the aforementioned architectural drawings.

Expanding the scope of object interpretation based strictly on architectural quantitative characteristics can be done in the field of tectonics, emphasizing the relationship between architectural features and materials and properties, as well as the structural potential of the elements made from them. However, this relationship remains somewhat one-sided. In Gottfried Semper's approach, using the right material means meeting formal-functional expectations or, further, imbuing purely material form with life [7]. Contemporary theorists like Kenneth Frampton, while recognizing architectural interpretations as works of art, move away from building analysis based solely on representation theory [8], perceiving the physical object as a result of three fundamental shaping factors: topos, typos, and tectonics instead. Such an understanding of tectonics encompasses many factors constituting architecture. Still, it omits the aspect of the construction process, including tools mentioned in the introduction, which are essential from the perspective of presented discourse. Materiality in these architectural concepts is significant, yet a defining transcendent factor – inherently unmeasurable, be it divine, based on laws of nature, or coming from an overarching idea shaping design intentions is always present. In other words, formal and conceptual aspects go hand in hand, but the latter always plays a leading role.

To some extent, contemporary interest in the fabrication process fills this gap, moving away from focusing solely on its outcome. One of the branches of this interest points to anthropological connotations of fabrication—material shaping of an artifact with all its contexts, including tool-related aspects. This trend also applies to architecture, including historical perspective, previously almost absent in this aspect. In the book "Making: Anthropology, Archaeology, Art, and Architecture," Tim Ingold suggestively shows this change in approach: "Building is an activity; it is what builders do. Add the article, however, and the activity is brought to a close. Movement is stilled, and where people had once labored with tools and materials, there now stands a structure – a building – that shows every sign of permanence and solidity" [9]. The building indicated by Ingold has been the primary, static subject of analysis so far, rarely leading to reflections on the process and tools. The approach presented in this paper, referring to additive manufacturing, necessitates revising static perceptions of architectural objects, revealing connections between the measurable parameters and the dynamic production process.

The use of additive manufacturing processes in architecture creates convenient opportunities to trace the relationships between architectural artifacts and the tools used to produce them. Analyses of this type of relations in historical terms have been difficult because the language of recording an architectural idea used in the design process, that is, drawing, had to be appropriately translated into the language of execution – from a kind of abstraction to the tangible, in order to result in the construction of a building. It resulted in a kind of conceptual gap. This gap has been the subject of many researchers' inquiries and was succinctly summed up by Robin Evans: "Architects do not make buildings, they make drawings of buildings" [10]. However, suppose we assume that nowadays architects create digital models instead of drawings. In that case, the information content, but above all, the possibility of transcoding such a model (also to a code interpretable by a fabrication tool), results in a direct relationship between the carrier of an idea (the model) and the fabrication process (physical implementation with AM production). As William Mitchell notes: "The integration between digitally augmented design and digital manufacturing (...) bridges the gap between design and production that emerged when architects began to create drawings" [11].

In additive manufacturing, this gap is even smaller, as the transcoding of digital data into physical artifacts is automated. The only thing between the model and its realization is a simple "start" button press. It is a connection that is more direct than in the case of other digital manufacturing methods [12]. A perfect example of this relationship is the Digital Grotesque II project by Michael Hansmeyer and Benjamin Dillenburger, designed and commissioned by the Pompidou Center in 2017. The digital model describing this pavilion, with a volume of about 300 by 200 by 345 centimeters, consisted of 260 million surfaces forming a grid of polygons, which at the production stage was represented by 42 billion voxels with an edge length of fewer than 0.5 millimeters [13]. The unimaginable precision of the design was dictated by the production technology with the resolution, or height of the layer, of 0.28 millimeters.

The features of additive fabrication and the characteristics of its use in architecture allow us to visualize and trace the relationship between architectural artifacts and the tools used to produce them. The authors investigated this relationship through strictly quantifiable, corresponding geometrical parameters describing both elements. Subsequent chapters discuss the method of the research conducted, the presentation and commentary of the results, and the discussion on the implications of the research.

Research Method

The study was conducted in three stages. The first was the creation of a catalog of relevant cases. A broad compilation of potential architectural objects produced using AM between 2004 and 2021 was created. Information sources about these objects were two-fold: internet sites monitored synchronously using Google search and Google Alerts functionality, and the Web of Science and Scopus databases, where a literature review was conducted asynchronously at two-year intervals.

In both cases, the search terms were „3d printing/additive manufacturing" with the operator „AND architecture/construction/design". In the second source, records were limited to the fields of Building and Construction and Architecture. Over a hundred cases of AM architectural objects and nearly a thousand scientific articles on the topic were identified. For all recognized cases, a selection criteria set was applied, including:

- **time criterion** – object realization between 2004 and 2021;
- **content criterion** – architectural objects as whole buildings, their modules, or elements;
- **implementation criterion** – objects had to be produced entirely, partially, or at least in the form of a physical prototype;
- **scale criterion** – a reference to the previous criterion – realization or prototype had to be produced at a 1:1 scale;
- **direct manufacturing criterion** – the additively manufactured object is a final product made from the target material.

Following the above criteria, 82 relevant cases of architectural objects manufactured using additive methods were selected. A dataset including general information, architectural and technological characteristics, and graphic documentation was created for each case.

During the analysis, significant geometric parameters of the object were considered, particularly:

- **object size** – maximum length, depth, and height;
- **module size** – maximum dimensions: length, depth, and height of individual modules composing the object if it consists of discrete elements;
- **detail resolution** – minimum distance between control points of a curve or NURBS surface, allowing for description of given geometry without loss for detail reproduction. Only the geometries of the studied cases resulting from designer decisions, e.g., object shape, were subject to interpretation. Aspects resulting from technology, such as shape/infill layout, were omitted.

Parameters related to technology were also analyzed:

- **working area** – maximum dimensions: length, depth, and height of objects possible to produce using a given technology or device;
- **technology resolution** – maximum resolution at which a given device can produce objects. If discrepancies in the resolution of a specific technology occurred horizontally (on a plane) and vertically (layer thickness), the larger value was used (smaller dimension).

All the above parameters were expressed in centimeters. Exceptionally, due to the scale of presented cases, volumes were expressed in cubic meters.

Subsequently, collected architectural parameters were analyzed quantifly. These analyses included tracking individual and mean values characteristic distribution in the collected cases over time, as well as calculating the global median and estimating the emerging linear trend. Due to a large spread of values, in this last type of analysis, a trimmed mean method was applied – in years when four or more cases occurred, extreme cases (minimum and maximum values) were omitted.

In the third stage, two selected mutual data types were compared, creating ratios further analyzed in the same manner as in the second stage. In both cases, these ratios were expressed as a percentage, which could be interpreted as a degree of the tool's potential use. These two were:

- **Scale Indicator (SI)** – the volume of object modules to the maximum volume resulting from the tool's work area;
- **Detail Indicator (DI)** – the resolution of the detail to the tool's resolution.

The results of the second and third stages of the described study method are briefly discussed in the subsequent two chapters.

Quantitative Study

The first of the discussed data, the object's size, represents most directly the extensive spectrum of additively manufactured architectural objects (Chart 1). Their volumes range from 0.004 to 6300 cubic meters. The lower boundary is set by certain early experimental solutions where individual architectural elements were fabricated. Examples are Planter Brick by Emerging Objects, Building Bytes by Brian Peters, and PolyBrick 1.0 by Jenny Sabin Lab. None of these objects exceeds a cubature of 0.01 meters. The upper limit is determined by entire buildings, such as the Nanjing Happy Valley Theme Park Gate, completed in 2021, which occupies a volume of 6300 cubic meters. However, as many as 23% of all cases fit within one cubic meter, while only 10% present large-scale solutions above 1000 cubic meters. The median volume equals 27 cubic meters. At the same time, the trend line identified for the collected data shows a strong upward trend. The trend line suggests approximately a 300% increase in object volume per decade, reaching almost 550 cubic meters in 2021.

A similar upward trend is shown by the trend line estimation regarding module sizes (Chart 2). In this case, the predicted size growth is slightly over 200% per decade, reaching close to 30 cubic meters by the end of the study period. The lower value of this parameter of 0.001 is, again, set by projects from Emerging Objects and Jenny Sabin Lab. Star Lounge and PolyBrick 2.0, respectively. The upper value reaches 812.9 cubic meters. Such large modules can be produced by Apis Cor and WinSun platforms dedicated to large-scale concrete printing. It should be noted that while the documentation of the Apis Cor tool's implementation in the construction of the Dubai City Hall in 2019 does not raise doubts about its maximum workspace, the photographic documentation of the cases in which WinSun's tool was used seems to contradict the declared values. These extreme cases of over 100 cubic meters volume modules constitute only 5% of all analyzed objects, which may indicate that the actual range and the trend line, resulting from the averages, are smaller. In 50% of cases, the module size does not exceed one cubic meter, and the median is precisely 0.97 cubic meters. Another 30% corresponds to a capacity of 27 cubic meters,

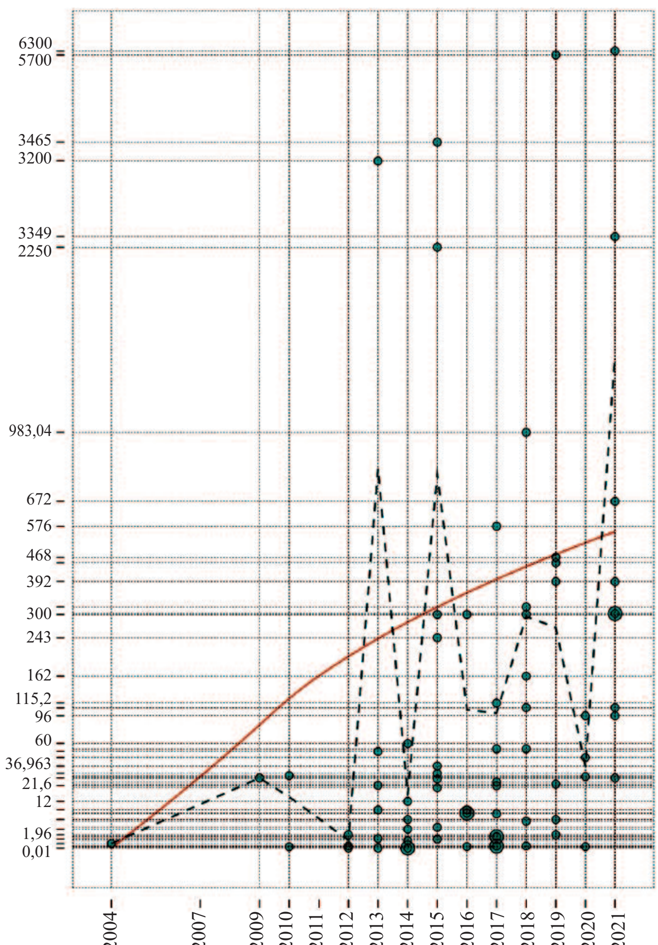

Fig. 1. The volume of the examined cases [m^3]. Each circle corresponds to one case. Dashed blue line – averages. Orange line – trend function. Note: logarithmic vertical scale *Fig. author's*

Rys. 1. Kubatura [m^3] badanych przypadków. Każdy okrąg odpowiada jednemu przypadkowi. Linia niebieska przerywana – przebieg średnich. Linia pomarańczowa – funkcja trendu. Uwaga: skala pionowa logarytmiczna *Rys. autorzy*

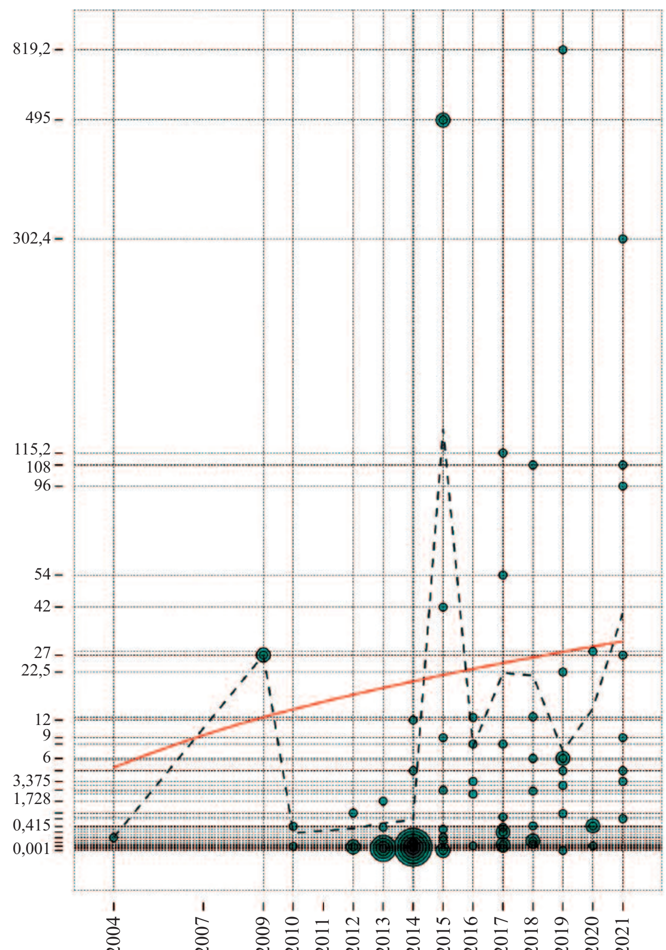

Fig. 2. The volume of case modules [m^3]. Each circle corresponds to one case. Blue dashed line – averages. Orange line – trend function. Note: logarithmic vertical scale *Fig. author's*

Rys. 2. Kubatura [m^3] modułów przypadków. Każdy okrąg odpowiada jednemu przypadkowi. Linia niebiska przerywana – przebieg średnich. Linia pomarańczowa – funkcja trendu. Uwaga: skala pionowa logarytmiczna *Rys. autorzy* corresponding to the aforementioned median value of the total object's size.

The last architectural data traced was the size of the detail. This domain ranges from 100 micrometers to 50 centimeters, with a median of 2 centimeters. The low value of the domain is set by Nematox System by Holger Strauss, Digital Grotesque by Benjamin Dillenburger and Michael Hansmeyer, and Trabeculae Pavilion by CREATE lab directed by Roberto Naboni. It is worth noting that 14% of all the cases present details of 0.5 centimeters, and 25% are even smaller. At the same time, it should be emphasized that for 15 cases, it was impossible to recognize any detail other than one resulting directly from material or manufacturing technology. These were simple walls with possible window or door openings. For these cases, the upper domain value of 50 cm has been assigned, which is the maximum thickness of these walls. The trend line of this parameter presents a descending behavior, a decrease in the size of the detail, and, hence, an increase in its resolution over time. For the collected data in the discussed period, the value determined by the trend line decreased by half to about 12 centimeters. Supplementary trend line analysis was conducted where the abovementioned detail-less cases were excluded. In this instance, a trend line with the same trajectory was obtained. However, the final detail's size was at most 5 centimeters in this instance.

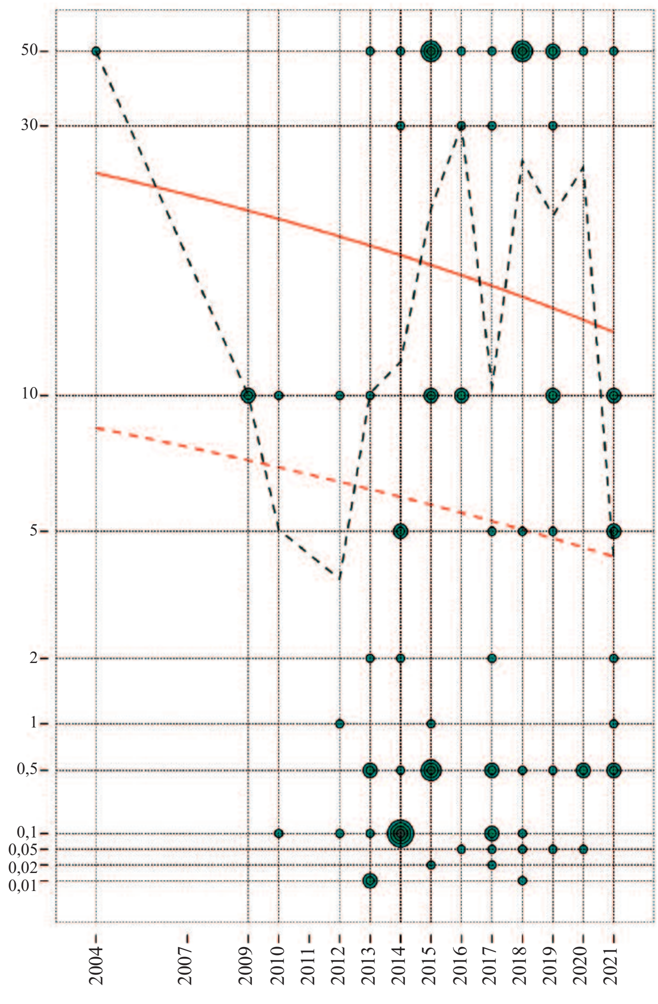

Fig. 3. The detail size of the discussed cases [cm]. Each circle corresponds to one case. Dashed blue line – averages. Orange line – trend function. Red dashed line – trend function for excluded cases

Fig. author's

Rys. 3. Rozmiar detalu omawianych przypadków [cm]. Każdy okrąg odpowiada jednemu przypadkowi. Linia niebieska przerywana – przebieg średnich. Linia pomarańczowa – funkcja trendu. Czerwona linia przerywana – funkcja trendu dla wykluczonych przypadków

Rys. autorzy

ComparativeStudy

Geometric architectural data discussed in the previous chapter were compared with analogous data concerning manufacturing technologies. This type of analysis stems from the authors' assumption that the appropriate use of a tool, its scale, and its detail should correspond to the expected characteristics of the produced object. As described earlier, the comparative analysis involved calculating and examining two indicators: the Scale Index (SI), where the volume of the module was compared with the maximum working space of the AM tool on which it was produced, and the Detail Index (DI), which illustrates the relationship between the object detail size and the native resolution of the technology.

The first indicator – SI – aimed to determine the extent to which technological constraints dictate the size of additively manufactured building modules. As observed (Chart 4), the trend line is relatively flat throughout the study period, ranging from 25% to 38% utilization of the maximum tool workspace. It should be emphasized, however, that these values may be inflated, as nearly one-third of all cases utilize no more than 10% of the workspace, and only 15 cases utilize it in more than 50%. In 9 out of 82 cases, the WS value ranged from 90% to 100%. The median for all cases is 21%,

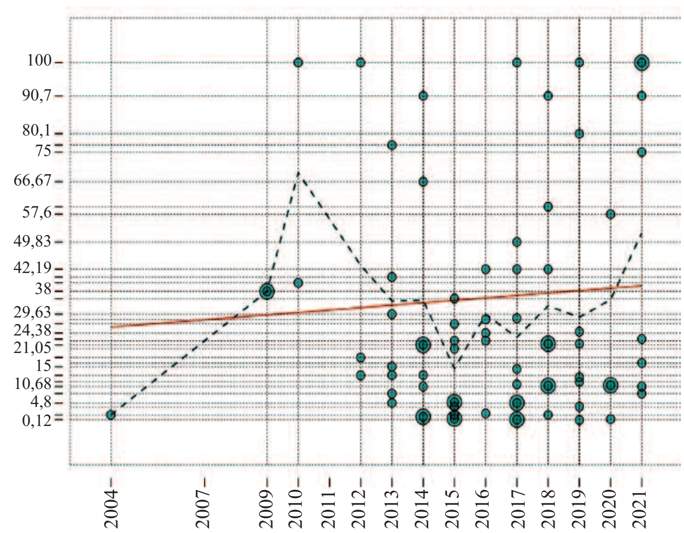

Fig. 4. Scale Indicator (SI) expressed as the ratio of the volume of the manufactured object to the maximum working area of a given technology

Fig. author's

Rys. 4. Wskaźnik Skali (WS) wyrażony jako stosunek objętości wytworzonego obiektu do maksymalnego obszaru roboczego danej technologii

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and the average is 29%. Since the results raised some doubts, the scale index values were further analyzed concerning tool workspace size intervals defined by successive powers of the number 10 – from 0.001 to 0.01, from 0.01 to 0.1, and so on up to the range of 1000 to 10000 cubic meters (Chart 5). In this case, the overall trend decreases, indicating that the larger the workspace, the smaller portion is used. At the same time, looking at the averages, a higher scale index value can be observed in tools with a workspace of up to 0.1 cubic meters and a range from 10 to 1000 cubic meters. Significant decreases in WS are visible in the ranges from 0.1 to 10 and above 1000 cubic meters.

The second indicator – DI – suggests rapidly increasing utilization of the capabilities arising from the resolution of tools compared to the complexity level of designed details (Chart 6). The trend line shows an annual increase of 2% and reaches nearly 38% in 2021. The median and mean values are

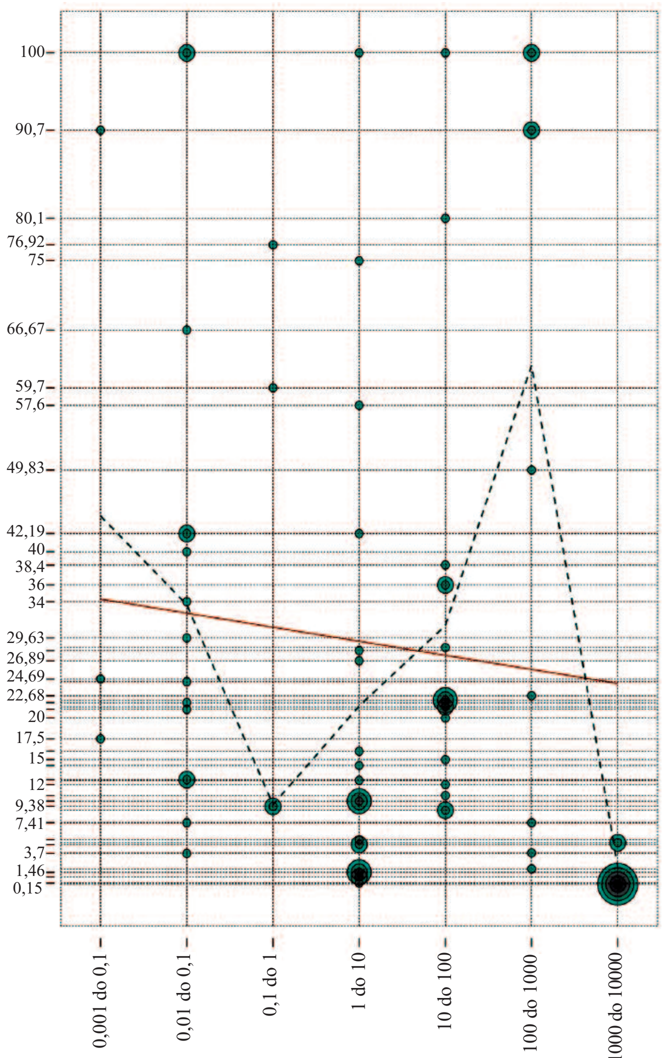

Fig. 5. Scale Indicator (SI) in relation to the ranges of the maximum volume of the tool's working area, expressed in cubic meters

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Rys. 5. Współczynnik Skali (WS) w stosunku do przedziałów maksymalnej objętości obszaru roboczego narzędzia wyrażonej w m3

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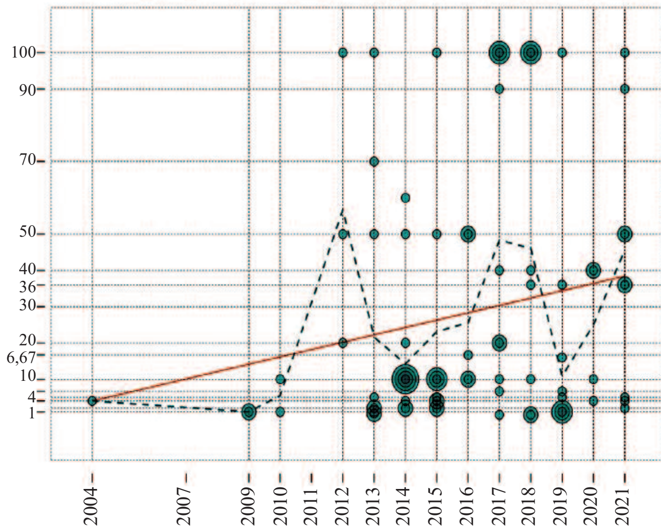

Fig. 6. Detail Indicator (DI) expressed as the ratio of the resolution of the design detail to the maximum resolution of the technology

Fig. author's

Rys. 6. Wskaźnik Detalu (WD) wyrażony jako stosunek rozdzielczości detalu projektowego do maksymalnej rozdzielczości technologii

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10% and 30%, respectively. This disproportion led to additional comparisons where WD values were analyzed in relation to tool resolution domains. The results of this analysis were inconclusive, as most cases fell within the ranges of 0.01 to 0.1 and 0.1 to 1 (in centimeters), with the majority of values evenly distributed between extreme values, below 10% and above 90%

Conclusions, Discussion

The conducted case study demonstrates a wide range of projects utilizing additive manufacturing methods. The criteria for case selection alone indicate that AM should be perceived as a full-fledged manufacturing method in architecture rather than experimental or solely prototyping tools.

The quantitative study of module sizes showed that between 2004 and 2021, their size did not change significantly. Furthermore, the comparative study clearly indicates that increasing the maximum tool workspace is associated with a decrease in the efficiency of the technology, as the available workspace is utilized to a lesser extent. A perfect example described in the literature addressing this issue is the aforementioned Digital Grotesque project. In this project, although the technology's workspace allowed for the creation of a volume of 200 by 800 by 100 centimeters, all the modules were within dimensions of 120 by 40 by 80 centimeters. Ease of transport, assembly, and post-production of elements dictated this design decision.

The quantitative study demonstrating increasing detail resolution is a harbinger of better understanding and mature utilization of technology, namely creating a closer connection and aggregative relationship between the manufacturing tool and the designed object. This argument finds further confirmation in the results of the comparative analysis, which indicate an increase in the detail index over the study period. On the other hand, the analysis of the detail index concerning the tool's resolution suggests that the utilization of AM potential results from a conscious, educated designer's decision rather than a general trend. The fact that most cases are distributed near the extreme values of WD spectra highlights contrasting approaches: those in which manufacturing technology is used reflexively, detached from the design method, and completely opposite, in which tool capabilities are one of the factors defining the project.

An interesting observation indirectly arising from the above conclusions is the relationship between the technology's workspace and its resolution. The average SI value initially is around 40%, then drops drastically and gradually rises to 60%, only to drop below 1% eventually. These drops are related to a boundary state, above which the technology's resolution does not allow for practical utilization of the offered workspace due to economic factors and production time. Devices with a workspace up to 1 cubic meter are typically FDM (fused deposition modeling) solutions, where the resolution, derived from nozzle size, is about 0.01 to 0.03 centimeters. Above 1 cubic meter and for a maximum value of 10,000 cubic meters, various proprietary extruders with nozzle diameters of about 1 – 2 centimeters are used, mounted on mobile platforms or industrial robots. The substantial drop in SI occurs when the volume is a thousand times larger than the tool's resolution – 0.1 to 1 cubic meter for a typical FDM resolution of 0.01 centimeters and from 1000 to 10000 cubic meters for a 1-centimeter non-standard material extrusion (ME) tool. This is because simultaneous complete utilization of scale and detail potential would result in very long work times and technological problems arising from, for example, low manufacturing error resistance. An error within a smaller module implies the need to reproduce only it, not the entire object.

Summary

As briefly presented, the analysis of tool aspects (in terms of manufacturing tools used on the construction site) and building erection process aspects is an interesting field of research, hitherto almost unexplored in relation to architectural design. The design process, treated as a conceptual activity translated into the physical realities of building construction, had to be mediated by the concept's record – drawing or, at the early stage of digital techniques application, a virtual model. Only in the next step was further translation into a physical artifact on the construction site performed. It does not mean, of course, that architects were unaware of the material and manufacturing process, as evidenced, for example, by the mentioned art of stereotomy. However, only the digitization of the manufacturing process allowed for the direct expression of the architectural design concept in the object's fabrication, thereby enabling comparative analysis of measurable artifacts and technology parameters. It also happens because the specificity of additive manufacturing offers a relatively wide range of both scales in which tools operate and their accuracies, allowing for a comprehensive quantitative comparative analysis. This analysis, in turn, enables pointing out cases where an in-depth understanding of manufacturing technology was a conditioning factor in design decisions (manifested in the artifact's quantitative parameters). In this way, by operating quantitatively, one can refer to the quality of the design process, fully utilizing the potential of available capabilities.

The method presented in this paper can be applied to subsequent design implementations utilizing additive manufacturing, as well as other manufacturing methods, by comparing defined scale and detail coefficient parameters while maintaining an awareness of the crucial role of a direct connection between the design's record and its manufacturing method.

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