Review

Rationalization methods in computer aided fabrication: A critical review

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ABSTRACT

Rationalization is widely recognized as an important design strategy in contemporary architectural projects, especially in projects with complex geometries, built using digital fabrication processes. However, an up to date review of the rationalization strategies used in these projects, their place in the design sequence and their relation to digital fabrication processes has not been conducted. The purpose of this review is to identify the rationalization strategies used in architectural projects in the practice and the academia.

This paper presents the results of a systematic review of over 500 papers describing rationalization and digital fabrication in contemporary architecture. Using the data gathered in the review, we show that the capabilities of the fabrication machinery used are the most frequently encountered rationalization constraint in realized architectural projects. Additionally, we describe a new taxonomy for rationalization strategies, which incorporates functional information with the temporal information described by traditional classifications. Using this taxonomy, we identify trends within the industry and the academia and point to the growing popularity of parametric co-rationalization approaches. We conclude by discussing promising rationalization approaches for future research.

1. Introduction

In recent years, advances in computational design tools have allowed architects to design projects with increasingly complex geometries. Some of these shapes have proven to be difficult and expensive to realize, even using state of the art digital fabrication processes, and architects have often needed to alter them according to the constraints of fabrication. The process of making a complex design feasible (possible to fabricate within the limitations of available machinery) and affordable (comparing it to the cost of a “regular” design) by altering its geometry is often referred to as architectural rationalization. This paper presents an up to date review of architectural rationalization, focusing on its development in a decade where parametric modeling and Computer Numerically Controlled (CNC) fabrication processes have been adopted by the architectural discipline and the building industry.

1.1. A brief history of architectural rationalization

Until the age of Humanism, the designer of a building was also responsible for the realization of his design, making the practicalities of construction an inherent consideration in any design decision [1]. This deep connection between design, structure, materiality and realization is apparent in masterpieces such as the Pyramids, the Pantheon or any of the great Gothic cathedrals, where the contemporary building capabilities were pushed to their limit.

It is with the separation between the architect and the builder, as it was advocated by Alberti, that the disciplines of structure and construction split from the stylistic, aesthetic craft of the architect [2]. Geometry, already a key architectural concept, further evolved as the basic tool for communication between the different disciplines as well as a mode of analysis for the design. The need for rationalization arose when designers started leaving the comfort zone of traditional geometry, easily projected onto the drawing plane, and introduced more complex shapes and forms. These new geometries were both difficult to describe using traditional notation systems, hard to analyze structurally, and difficult to build using existing methods.

Gaudi, one of the early pioneers of geometric rationalization, was instrumental in introducing complex geometries into the architectural discourse. After his free-form, undulating design of the Casa Mila almost bankrupted the contractor (who agreed to build it within a fixed price), Gaudi developed a system of working with ruled surfaces for his later designs, including the Sagrada Familia [3]. This system, based on shapes such as hyperboloids which could be mathematically described, better conforms to the practicalities of construction without compromising the genius of Gaudi’s design [4].

The use of geometry to rationalize works of great visual complexity is easily apparent in the works of the great architect/engineers of the
mid-20th century. Candela, for example, was a great believer in hyperbolic paraboloids, as their double curved surface is both very stiff and relatively easy to construct using wooden planks as formwork for re-enforced concrete [5]. Dieste, on the other hand, used catenary surfaces for the creation of ultra-thin shells made from brickwork. These shapes are highly rational in the sense that they are adapted to both the structural requirements and the practicalities of bricklaying. He said that designing complex structures reminds us of the primary aspects of architecture: it forces the designer to become a builder [6]. These architect/engineers are related to the great architect/builders of old in the sense that they assumed full responsibility for the realization of their design. Rationalization, for them, was not only an ideology or an artistic style but also an economic necessity.

A different approach to the subject of rationalization can be seen in Le Corbusier's Philips pavilion (1958). In this case Le Corbusier's initial organic design had to be translated into a ruled geometry by Xenakis, an engineer, to make it realizable. The scandal following the publication of the pavilion under Le Corbusier's name alone resulted in an untypical admission of co-authorship by the great master [3]. Another classic example is Utzon and the shells of the Sydney Opera House (1956–1973). As described in detail in [7], Utzon had to change his original, free-form design because the manufacturers were simply not able to fabricate it. With the help of the ARUP engineering firm, he “disciplined” his design by translating the free-form surface into repetitive, spherical segments, which were possible to produce. The seven-year-long rationalization process was also one of the first instances where computational geometry was used in the architectural context (ibid). This seminal process is often considered the direct predecessor of contemporary rationalization, a tensioned discourse between design, engineering, and computation.

1.2. Two decades of computational architectural rationalization

In the 1990s, Gehry Partners complex, free-form designs were paramount in introducing computer aided 3D modeling and manufacture to the traditional architectural practice. The contemporary academic discourse around rationalization is often traced to the discussion of his works at the time. Lindsey [8] was one of the first writers to use the term rationalization in the architectural context. He described the process of translating Gehry’s complex designs into constructible geometry as a process of rationalization, which he defined as the introduction of mathematical “rules of constructability” in order to legitimize “crazy” designs. In his Ph.D. thesis, Shelden [9] described the rationalization process conducted in Gehry Partners as one where handmade physical models are approximated by digital models with programmed geometric constraints which guarantee their constructability. He credited the development of CATIA V5, a fully parametric associative modeler with this new approach and envisioned advanced form-finding methods based on this process.

Whitehead [11] used the term rationalization to describe how fabrication logic is introduced into a design by Foster + Partners. He differentiated between projects that were designed using free-form surfaces and then translated into easy to construct arc based geometry and projects which were deliberately designed using constructible geometry such as torus patches or ruled surfaces. Whitehead used the terms post-rationalization and pre-rationalization to categorize rationalization methods according to when they are performed in the design process. He advocated the use of pre-rationalized approaches as they achieve a high degree of control that resolves many design and production issues. Fischer [12] formalized the discussion by defining rationalization as the process of approximating a shape using a well-defined generative algorithm. He also attributed the temporal division of rationalization strategies to Whitehead, adding another temporal category called co – rationalization in which the compositional system is redefined throughout the design process (ibid).

Hesselgren [13] referred to pre-rationalization as the process of embedding constraints into the geometry by designing using fundamental shapes. He claimed this method is preferred over other types of rationalization, as it achieves higher performance results. Attar [14] stated that in pre-rationalization geometric constraints pre-determine the building final shape. He illustrated this process by describing the design of the Sage Gateshead center by Foster + Partners, where the design was limited to toroidal geometry (see Fig. 1). He also defined post-rationalization as a process where the design is retroactively simplified to be more constructible. Pottman [15] referred to pre-rationalization as construction-aware design and to post rationalization as design optimization. Dritsas [16] pointed out that post-rationalization relies on intensive computational optimization. He gives Gehry’s Walt Disney Concert Hall as an example of such a process (see Fig. 1).

1.3. Rationalization in other fields

The study of rationalization is not unique to the field of architecture, and is widely practiced in the fields of construction engineering and product design. In the construction industry, value engineering is a traditional method of making a design more affordable by discarding expensive elements not necessary to its function [17]. Architectural Rationalization, on the other hand, will attempt to modify these elements as little as possible so that the original design can be maintained within the affordability of fabrication. A different engineering approach is often related to as buildability or constructability and was first brought to light in the 1960s [18]. Buildability is defined as “the extent
to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building” [19]. Today, buildability research is focused on policies, checklists, organizational and contractual measures, reviews, system modeling and Building Information Technology [20]. An approach tending to preclude architects from the discourse [21].

In the field of product design, design for manufacturing – DFM, has been a subject of research since the 1980s [22]. Youssef [23] presents many definitions of the term, including “The Philosophy and practice of designing a product for optimal fit to a particular manufacturing system”. Liu and Yang [24] highlighted the importance of practicing DFM early in the design process and described different strategies for different fabrication processes. Traditionally, the manual art of building was very different than the industrial practice of manufacturing. However, as the architectural construction transitions from traditional manual labor to digital fabrication processes, some of the insights of DFM might be incorporated into architectural rationalization- admitting the marked differences in scale, complexity, and repetition between the disciplines.

1.4. Reviews of architectural rationalization

In 2012, Fischer [3] published a review of rationalization in architecture, providing historical depth and categorizing projects from the early 2000s according to the temporal definition. His review does not cover newer projects, digital fabrication or general rationalization methods, and one purpose of our review is to address these gaps.

In 2015, Pottmann et al. [25] published a review of rationalization from a mathematical standpoint. They claimed that fields such as differential geometry, discrete mathematics, numeric optimization and computer graphics processing are all highly relevant to the rationalization discourse and group them into a field of research they refer to them collectively as “architectural geometry” [26,27]. Their review categorizes algorithms according to the type of geometry which is being rationalized (developable, double curved, etc.), or the target of the rationalization (structure, paneling, repetition, etc.). While their review covers many contemporary built examples of each category, it does not actively question the place of rationalization in the design sequence, nor the relationship between digital fabrication and rationalization. Our review is focused on this relationship, which we perceive as a key issue in the discourse [28,29].

We chose to use a systematic approach to data gathering, focusing on papers published in the last decade. Our review methodically collected data on aspects such as relation to fabrication processes, timing in the design sequence, type of strategy used, and the identity of the agency performing the rationalization. It also differentiated between the academia and the practice, and between “general” rationalization methods and ones developed for realizing specific projects.

This paper starts with a description of the systematic review method used. The next section presents the research findings, starting from general findings regarding digital fabrication research and focusing on findings regarding rationalization. In this section, we describe a new taxonomy of rationalization strategies at the end of this section. The paper concludes with a critical discussion of the findings, focusing on the current state of fabrication and rationalization research and pointing out directions worth pursuing in the future.

2. Review methodology

We conducted this review using a systematic review methodology common in the medical, computational and social sciences. Systematic reviews are often used to obtain an accurate picture of the research in a field where significant amounts of data have accumulated, without comprehensively reading all of the published studies They can be used to identify gaps in current research paradigms and suggest promising new research vectors [30]. The specific methodology used for this review is based on general guidelines for conducting a systematic review suggested by [31], which enables researchers to set up screening parameters that filter the studies chosen for the review without comprehensively reading the entire body of published work. The systematic methodology was used to achieve a balanced, well-rounded picture of the current research and practice in the field of rationalization for fabrication. It also allowed us to achieve a quantitative analysis of the results and decrease the publication bias inherent in such efforts. The review process is comprised of three main stages:

1. Searching for literature and constructing the initial Database.
2. Screening of the initial list of papers (abstract review).
3. Data extraction from the screened papers (full-text review).

2.1. Searching for literature and constructing the database

Although Digital Fabrication became a prime subject of architectural research before the turn of the new millennia, rationalization was only mentioned by a few writers, mainly practicing architects working with Gehry or Foster [8,11]. It is only around 2006, with papers such as [12,13,32,33] that the subject of rationalization becomes an established academic research interest, and the discussion rich enough to warrant a serious review. Thus, our paper documents the intensive discussion regarding fabrication and rationalization within the last decade.

As an initial database for this review, we searched in the Scopus database for items containing the words ‘fabrication’, ‘manufacturing’ or ‘rationalization’ in their title, abstract or keywords. To focus on papers with a good chance at being relevant to the subject, the search was limited to the three leading academic journals in the field (Architectural Science Review-ASR, Automation in Construction-AIC, International Journal of Architectural Computing-IJAC), and a popular curated journal specializing in digital architecture (Architectural Design). We balanced these with an equal number of papers published in the proceedings of three specialized conferences on the subjects of fabrication, computer graphics, architectural geometry (Fabricate, SIGGRAPH, AAG) and a similar amount of papers sourced from a regional conference about digital architecture in general (ACADIA). The systematic methodology enabled us to achieve a balanced representation of the research in the field by excluding some sources without comprehensively reviewing them, as a full literature review would have required.

The search resulted in 501 papers that contained these terms, comprising the initial database for this review. During the different review stages, we removed 45 of these papers from the database, mainly because they described projects which appeared in other papers included in the review. Table 1 describes the sources and years comprising the final database used in this research.

2.2. Initial screening of the database– abstract review

A typical preliminary stage in conducting systematic reviews is the manual of screening of papers, conducted by reading their abstracts and comparing them to well-defined inclusion & exclusion criteria [30]. During the screening stage, we collected data about the following categories: Topic, authorship, fabrication technology, main material, and scale from all the papers in the database.

Table 2 describes the topics of the papers whose abstracts were reviewed. To survey both the theoretical and the practical aspects of rationalization, we decided to include in the next stage of the review only papers describing general rationalization methods or papers describing architectural scaled projects. While we set aside papers with other subjects, the data collected in provided interesting information regarding the state of fabrication research in general, described in Section 3.1.
the rationalization strategy used and the type of constraints targeted. In rationalization methods. Both categories were analyzed with respect to pics: design and construction of digitally fabricated projects or general

### Table 2

Main topics of all papers considered for the review.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Description</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rationalization</td>
<td>General rationalization methods.</td>
<td>23</td>
</tr>
<tr>
<td>Project</td>
<td>The design and realization of an architectural scale project.</td>
<td>102</td>
</tr>
<tr>
<td>Process</td>
<td>Describes a new fabrication process, without a full-sized prototype.</td>
<td>133</td>
</tr>
<tr>
<td>Code</td>
<td>Algorithms, software, and plugins related to fabrication but not to rationalization.</td>
<td>17</td>
</tr>
<tr>
<td>Technical</td>
<td>Technical/Engineering subjects without architectural development (including BIM)</td>
<td>33</td>
</tr>
<tr>
<td>Education</td>
<td>Dealing with the instruction of Digital Fabrication in the academia.</td>
<td>29</td>
</tr>
<tr>
<td>Culture</td>
<td>Regarding the effect of Digital Fabrication on modern culture and society.</td>
<td>15</td>
</tr>
<tr>
<td>Art</td>
<td>Art, sound and the use of CAM for modeling.</td>
<td>19</td>
</tr>
<tr>
<td>Performance</td>
<td>Sustainability, light, acoustic and climatic performance issues.</td>
<td>16</td>
</tr>
<tr>
<td>Design method</td>
<td>Regarding new (digital) ways to arrive at designs.</td>
<td>39</td>
</tr>
<tr>
<td>Material</td>
<td>Material oriented research</td>
<td>10</td>
</tr>
<tr>
<td>Dynamic</td>
<td>Adaptive, movable structures.</td>
<td>13</td>
</tr>
<tr>
<td>Other</td>
<td>Other subjects relevant to the field of Digital Fabrication but hard to categorize.</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>456</td>
</tr>
</tbody>
</table>

### 2.3. Data extraction from the selected papers (Full-text review)

In this stage of the review, we chose papers according to their topics: design and construction of digitally fabricated projects or general rationalization methods. Both categories were analyzed with respect to the rationalization strategy used and the type of constraints targeted. In the projects category, we also retrieved data regarding who conducted the rationalization and when it was conducted. In the rationalization category, we cataloged parameters regarding the type of interface suggested, and the geometric properties rationalized. Section 3.2 presents the findings from this analysis. The entire database can be found at http://dx.doi.org/10.17632/52bwtthkt7.2

### 3. Findings

This chapter presents findings from the different review stages. The first section describes processes and materials used in contemporary digital fabrication research and is based on findings from the abstract review stage. The next section focuses on projects and rationalization and is based on findings from an in-depth review of the relevant papers. The findings enable us to catalog rationalization practices in the industry and the academia and to illustrate recent trends in rationalization research.

#### 3.1. Findings describing digital fabrication in general

The main purpose of the abstract review was to exclude papers from the main study, focusing only on papers directly relevant to rationalization. While conducting this stage of the review we discovered information which illustrates the current state of fabrication research. The findings presented below document the use of fabrication processes and materials in all the reviewed papers.

#### 3.1.1. Materials & fabrication processes

Table 3 enumerates the appearance of fabrication processes and materials in the abstracts of the reviewed papers. Wood, steel, polymer,
and concrete are the materials most often mentioned. Likewise, 3-axis milling and additive manufacturing are the most popular fabrication processes. Cross-referencing materials with fabrication processes reveals that wood is typically mentioned in relation to milling processes and that this combination is the one most often encountered. Similarly, the data shows that 3-axis CNC cutting processes are usually mentioned in conjuncture with steel and that polymers and concrete are often mentioned together with additive manufacturing processes. We chose to present the data gathered here in its entirety because we consider it to be a useful reference for any research in the field of digital fabrication.

3.1.2. Robotic fabrication in contemporary research

Fig. 2 describes the combined appearance of robotic technologies as a percentage of the total identifiable techniques used by the academia and the building industry. By robotic fabrication, we refer to fabrication technologies such as milling, hot wire cutting, or filament deposition, mounted on industrial robotic arms. We can see that the total frequency in which these technologies were used has risen steadily over the last decade, and now surpasses all other fabrication processes combined. It is important to note that this trend was observed even though publications dedicated solely to robotics were not included in the review and that the word robot was not among the search criteria.

Fig. 2 highlights the different approach to robotics between the academia and the industry. It illustrates the significantly higher appearance of robotic fabrication in papers describing academic projects in contrast to papers describing projects from the building industry. On average, only 5% of the projects from the industry feature robotic fabrication while 32% of the collaborations between the academia and the industry and 45% of purely academic projects do so. Some of this difference may be attributed to a statistical error—only about 20% of the papers reviewed described projects from the industry. Nevertheless, these findings seem to indicate a fundamentally different approach to architectural robotics in the different sectors which will be further discussed in the conclusions.

3.2. Findings regarding rationalization methods

We collected the data presented in this section from papers describing rationalization methods or papers describing the design and construction of architecturally scaled projects. The findings presented below begin by reviewing the targets of rationalization methods. The next section describes the timing of the rationalization process. The last section uses the data gathered in the review to provide a new taxonomy of rationalization methods and describes the categories in the taxonomy using examples from the review.

3.2.1. Targets of rationalization processes

This section describes the frequency in which different constraints are mentioned in papers from both review categories: built projects and rationalization methods. The constraints appearing in Fig. 3 are grouped into several families: Fabrication constraints, Material constraints, Construction constraints and Design constraints. Individually, the capabilities of fabricating machinery are the single most common target for rationalization processes in the analyzed papers. Adherence to design geometry is the second most common. Material properties and dimensions also appeared frequently as targets for rationalization, as well as structural requirements. Most of the constraints are represented proportionately to the number of papers sourced from the relevant sector. However, construction-related constraints and some of the material constraints appear more in industry related projects.

Further scrutiny of papers describing abstract rationalization methods (i.e. methods not developed for a specific architectural project), shows that each of these methods can be placed on a spectrum describing the specificity of the method. On one hand are abstract geometric properties such as planarity of quad meshes, equal edge offset, repeatability, and developability. These abstract properties are known to be crucial for the production of building façade paneling and a significant amount of research has therefore been dedicated towards finding methods of designing with these types of geometries [14,15,33–39]. On the other end of the spectrum are a smaller amount of rationalization methods dedicated to specific digital fabrication processes such as 3-axis milling or hot wire cutting [40–42]. Other papers can be said to be somewhere between the two distinct edges, dealing with diverse issues such and combining “pure” geometrical approaches with specific machine related fabrication considerations [12,16,43–45].

3.2.2. Timing of rationalization processes

The review discovered that 85% of the papers describing the construction of architecturally scaled projects mention rationalization explicitly or implicitly. Table 4 relates to the traditional way researchers categorize rationalization methods: per their timing in the design sequence, often referred to as pre, post or co rationalization [8,12–14]. Using a purely temporal categorization, we divided the cases according to their relation to the design development stage. The table shows that in 35% of all the projects documented, rationalization was conducted before the design development stage, in 29% during the design development and 21% after the design has been finalized and tender had been issued. Table 4 also shows that the academia conducts rationalization much earlier than the industry, a fact clearly influenced by the different scales, materiality, personnel, monetary structure and the design/tender/build stages of the different sectors. Despite all these differences, we feel that in the case of architecture, academia must direct its research towards avenues potentially useful to the industry. Thus, a comparison between the sectors could point towards future avenues of research for the academia, one of the main purposes of this review.

To fine tune the analysis we decided to quantify the timing of rationalization processes in relation to the different disciplines. As shown in Fig. 4, academic researchers have a very strong bias towards pre-rationalization. Designers, engineers, and fabricators on the other hand, usually address rationalization during the design development stage, when the project begins to materialize. Fabrication specialists will address rationalization as soon as they are added to the team, which is usually towards the end of the process. The difference in the timing indicates a different overall approach to rationalization between the disciplines, which will be qualitatively explained in the next section by analyzing rationalization strategies in depth.

3.2.3. A new taxonomy for rationalization strategies

The classic, temporal distinction between rationalization methods was critiqued by Dritsas for not capturing the richness and variety of strategies existing in the building industry, nor assisting in choosing the right method for a specific project [16]. He suggested an alternative categorization, in which rationalization methods are divided per the type of strategy they use: description, analysis, and evaluation (ibid.). Conducting this review enabled us to suggest an integrated definition of rationalization strategies, which combines functional information with the classic temporal information.

Fig. 5 enumerates the different strategies within our taxonomy, differentiating between academic projects, projects from the building
industry and collaborations. In this new taxonomy, we divide the temporal category of Pre-Rationalization into two different design strategies: “Fabrication Driven Design”, in which designers actively use geometries which they know can be built using a specific fabrication process. “Fabrication Aware Form Finding”, in which computational methods help the designer discover geometries which fulfill fabrication constraints. Another category we suggest originates in the strategy Whitehead called Co-Rationalization [12] and we refine its definition to “Parametric Co-Rationalization”. In this type of strategy, parametric design tools control the entire design, allowing it to be adjusted as constraints are discovered. We have found that this type of rationalization strategy is the most common in the building industry.

3.2.3.1. Pre-rationalization: fabrication driven design. Pre-rationalization is often defined as a process in which logically applied constraints pre-determine the architectural geometry, limiting the design to a family of geometries which are known to be buildable [14]. We found that most of the pre-rationalized architectural projects encountered in the review used design processes aimed at the specific capabilities of locally available materials and fabrication equipment. Thus, We refer to this strategy as “Fabrication Driven Design”, a term used to describe “the correlation of…fabrication potentialities and constraints with design technology and methodology” [46]. It is a strategy in which the entire design sequence is based on apriori knowledge of a specific fabrication method, which becomes the main design driver. An example of such a strategy is illustrated in [40] who describe ways to design geometry so it can be cut with a robotic hot blade.

Fig. 6 shows how constraints related to materiality and fabrication capabilities influence the design of specific projects: On the left image, 3-axis milling capabilities and the bending properties of plywood dictate the shape of The Caterpillar Pavilion [47]. In the center, the possibilities afforded by robotic hot-wire cutting shape the Periscope Foam Tower [48]. On the right - robotic assembly abilities and material dimensions influence the form of the West Fest Pavilion [49]. Additional projects which use this strategy typically appear in the academia [50–59]. However, some interesting industry related projects using this approach can also be found [60–62].

The review indicated that current research into general methods for pre-rationalization is aimed at finding new ways to design easily realizable façade glazing systems. These methods introduce geometries such as Face-Edge offset meshes [37], Marionette meshes [35], interactive constraint modeling [34], or Isogonal molding surfaces [36].

![Fig. 3. Frequency of appearance of different fabrication constraints.](image3)

**Table 4** Timing of rationalization processes: number of cases and relative percentage of the total findings.

<table>
<thead>
<tr>
<th>Where/when</th>
<th>Before</th>
<th>During</th>
<th>After</th>
<th>Not mentioned</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Academia</td>
<td>29 (56%)</td>
<td>11 (21%)</td>
<td>10 (19%)</td>
<td>2 (4%)</td>
<td>52 (100%)</td>
</tr>
<tr>
<td>Collaboration</td>
<td>9 (36%)</td>
<td>6 (24%)</td>
<td>3 (12%)</td>
<td>7 (28%)</td>
<td>25 (100%)</td>
</tr>
<tr>
<td>Practice</td>
<td>6 (13%)</td>
<td>20 (42%)</td>
<td>13 (27%)</td>
<td>9 (19%)</td>
<td>48 (100%)</td>
</tr>
<tr>
<td>Total</td>
<td>44 (35%)</td>
<td>37 (30%)</td>
<td>26 (21%)</td>
<td>18 (14%)</td>
<td>125 (100%)</td>
</tr>
</tbody>
</table>

**Fig. 4.** Timing of rationalization processes: cases found per discipline.
3.2.3.2. **Pre-rationalization:** *pre-rationalization: fabrication aware form finding.* Another pre-rationalized approach is one in which fabrication constraints are used as targets in computational form-finding processes. This strategy is different from the previous one because the designer does not actively steer the design to any specific shape. Instead, an algorithm constructs a virtual space of solutions in which all shapes are buildable – what Menges and Schwinn refer to as the Machinic Morphospace [63]. By computationally exploring this space, it becomes possible to determine geometric configurations which satisfy all other design constraints and please the designer as well. We expand the term “Fabrication Aware Form Finding”, which was coined in relation to a specific relaxation algorithm by Maxwell to include all projects using this type of approach [64].

Fig. 7 shows projects that employ Fabrication Aware Form Finding to derive the design geometry. On the left image: Dynamic relaxation with embedded fabrication information determined the shape of the Utzon 40 Pavilion [64]. In the center: An agent endowed with fabrication awareness determines its optimal position in the Landesgartenschau exhibition hall [65]. On the right: Mesh relaxation determines overall geometry while agents form mesh triangles into fabricable strips in THEVERYMANY’s Under Stress [66]. This type of strategy is usually used in academic endeavors [42,67–85].

We also encountered some general, non-project related rationalization methods, which utilize this approach [12,14,39,86,87]. The methods suggested in these papers view the designer and the computer as “joint authors” of the resulting form, which is controlled using parameters fed into the form finding algorithm.

3.2.3.3. **Parametric co-rationalization.** This strategy is based on the coming-of-age of parametric modeling tools such as Grasshopper or Digital Project and their adoption by the architectural profession. Originally referred to as simply as co-rationalization [3,12,88], it is described by Ceccato as the holy grail of digital architecture [88]. It uses the inherent flexibility of parametric tools to calibrate the design as different fabrication constraints are discovered [89]. Parametric design has long been associated with the production of non-standard architecture [80,90]. It is a dynamic strategy, releasing the designer from the need to rationalize the design at any specific stage. It is typically a hybrid strategy, often mixing pre-rationalized assumptions and post-evaluated efficiency measures, allowing for manual or automatic optimization processes. Most of all it is a highly versatile strategy, able to accommodate many types of fabrication constraints in varied design sequences.

Fig. 8 describes projects using this strategy in the academia and the industry. On the Left: the aluminum cladding for Zaha Hadid’s Galaxy SOHO were repeatedly adjusted and optimized in a multi-staged co-rationalization process before and after the tender [88]. In the center: The designers of the FabPod workspace used Grasshopper as a design tool, which allowed them to defer the detailed design until the fabrication strategy was developed [89]. On the right – a complex hierarchical data design using Digital Project allowed the creation of this double curved wooden ceiling by Gehry & Partners. In this project, the use of parametric tools allowed a continuous upstream/downstream flow of information during the design sequence as fabrication constraints were discovered [91].
We found Parametric Co-rationalization to be the most commonly used of all the rationalization strategies for architectural projects appearing in the review, especially in the industry [32,48,54,92–110]. Surprisingly, very few papers describing general rationalization methods, provide tools which can be used during a parametric design process. These papers typically focus on either pre or post-rationalized approaches. Only very recently do we see the academia addressing the possibility of exploiting these methods during the design process [34,87].

3.2.3.4. Post-rationalization: optimization.
In the architectural discourse, the term optimization refers to a repetitive process in which designs are generated using a parametric definition, numerically evaluated using analysis/simulation and improved using a mathematical algorithm to search within the possible solution space [111,112]. In the context of fabrication, optimization refers to a post-rationalized process in which geometry is first designed without acknowledging fabrication constraints and later adapted to the chosen setup by computational procedures [14], a strategy used both in the building industry and in the academia.

On the left of Fig. 9, we can see the structure for Gehry’s Louis Vuitton Foundation, which was optimized towards hot and cold glass bending capabilities [113]. On the right, we see the result of an algorithmic optimization of the Eiffel Tower Pavilion glazing towards describing the geometry in developable conical strip patterns, which function well within the constraints of glazing fabrication [114]. Other examples of post-rationalized optimization can be seen in both the academia and the industry [115–120].

The frequent use of computationally intensive optimization in the industry can be attributed the fact that optimization algorithms have the ability to solve problems which are either hard or impossible to pre-determine, model or solve by other means – such as physical problems related to structure, thermal behavior, and acoustics. In general, post rationalization postpones fabrication related decisions to the construction detailing stage, which releases designers from the technical awareness often associated with pre-rationalization and conforms to established architectural workflows.

3.2.3.5. Post-rationalization: translation.
In this type of post-rationalization strategy, a third party translates the architect's original design model to a different computational medium, which better suits its fabrication setup. During this process, knowledge about the structure, materials, fabrication setup, and construction sequence lacking from the original CAD model is used to create a new, fabrication oriented digital model. As the original design is completely remodeled in this type of process, the similarity or tolerance between the two models is not guaranteed and preserving the design intent plays a crucial role in the creation of the new model. This translation from design into fabrication instructions naturally falls into the domain of industry related projects and is performed either by the fabricator himself or a by a fabrication specialist such as Designtoproduction [125], which are sometimes even credited as co-designers since their input is crucial and often changes the entire design.

On the left side of Fig. 10, we see the results of BEMO systems’ process of translating geometry into CNC fabrication instructions for sheet metal cladding. The success of outcome of their process depends on the ability of the original freeform geometry to accommodate the translation into ruled surface strips and the protruding seams between the strips [126]. In the Center: Designtoproduction translated SANAA’s flaying surfaces for the Rolex learning center into a detailed set fabrication instructions for hundreds of CNC-milled molds while keeping the result within an acceptable tolerance to the original design [125]. Right – The Richmond Oval Skating Rink was translated from a conceptual model into a complete fabrication setup including code and
custom machinery in a collaboration between the engineers and the fabricators. In this case, the architects only outlined the general form of the geometry and left the design-build firm the freedom to explore structural/fabrication solutions and develop the design accordingly [127].

In the practice, translation is strategy usually used by fabricators or fabrication specialists [128–132]. Academic research describing translation as a rationalization strategy include a method for translating double curved geometry into flat paneling [42] and a method for translating double curved geometry into ruled surfaces [45].

4. Discussion & conclusions

From the Gothic cathedrals to Le-Corbusier’s Domino house, architects have always practiced rationalization in one form or another. This review demonstrated how the advent of computational design tools and digital fabrication processes, has highlighted the process of rationalization of complex geometry During the last decade, rationalization ceased to be the exclusive practice of a few specialists and is now practiced by academics, designers, engineers, fabricators, and even by contractors. Using a systematic review methodology, we were able to derive a new taxonomy of rationalization strategies which we used to understand recent trends in the academia and the industry. As an unexpected contribution, the review also brought to light important aspects related to research into digital fabrication. The following sections discuss the findings described in the previous chapters and suggest promising avenues for future research.

4.1. Robotic fabrication in the academia and the industry

Fig. 2 demonstrated the difference between the swift adoption of robotic fabrication processes by the academia and their much slower appearance in actual construction projects. These findings might indicate an over-eagerness of the academia to explore a new medium, which is not necessarily based on the needs of the industry. A similar phenomenon was described by Bechthold, who documented the rise and fall of construction robotics in Japan in the 70s and 80s [133]. Bechthold goes on to point out that the field of industrial robotics and the software that controls them has greatly improved since, and that this time around, robots are here to stay. Our review shows some support for his claim by showing that industrial robotics have recently started to appear in collaborations between the industry and the academia. Thus, while they still hardly appear in projects from the building industry, a change might be forthcoming. However, to understand the real extent of the adoption of robotic technologies in the building industry, further research will be necessary.

4.2. Parametric co-rationalization

In Table 4, we demonstrated that rationalization is an important strategy in architectural scaled projects in both the academia and the industry. The two sectors tend to rationalize their projects in different times: before the detailed design in the case of the academia, during or after the detailed design in the practice. While the comparison between the sectors is difficult due to scale, personnel and monetary structure, we can provide suggestions for the reasons behind these apparent differences. In academic projects, the designer is typically also in charge of fabrication and has good cause to incorporate the constraints early in the process. In the typical design-bid-build process practiced by the industry, the involvement of fabricators before the tender is issued is rare [105,125] and the fabrication method is unknown until a later stage in the design sequence. This leads to a tendency to rationalize designs later, together with the engineer or a specialist, even though changes to the design at that time are less effective and harder to implement [134].

Fig. 5 illustrated the high popularity of an approach we call Parametric co-rationalization in the practice. It is an informed process of change and adaptation which starts early in the design sequence and is
developed until the physical fabrication [89,91]. The increasing use of this strategy is based on the growing capabilities and popularity of parametric tools such as Grasshopper, Digital Project or Generative Component to continuously adjust the design as fabrication constraints are discovered.

However, Section 3.2.3.3 demonstrated that rationalization methods developed in the academia are either pre-rationalized, intended as the primary tool for form generation, or post-rationalized, and deal with almost finished architectural designs. Somehow, we have neglected to develop general rationalization strategies which can be used during the design process, when they are most needed. This might be because standalone algorithms, functioning before or after the design process, are easier to implement. But tools such as these ignore the complexity of the architectural design process, where many different factors compete for the architect’s attention, and changes can be made at any given moment.

Thus, we believe that future research should be directed at introducing fabrication constraints during all the different stages of the design sequence, focusing on methods that complement the workflow the industry is accustomed to. Such tools should be able to function within a typical parametric design process, which also controls other aspects of the building’s design. Our conclusions corroborate those of Pottmann et al. [25], who argued that fabrication simulators should be integrated into modeling software in order to shorten the product development cycle.

4.3. Real-time rationalization strategies

In order to be useful in a design scenario, parametric co-rationalization strategies should be able to function in real time, constantly responding to adjustments in the design. Until 2010, papers describing rationalization methods did not attempt to develop methods which could be continuously adjusted during the design process. At the time, Pottmann stated that real-time computation of the algorithms necessary for rationalization is too computationally expensive and thus still a major research challenge [15].

However, recently developed methods have begun to harness the advantage of using real-time strategies in both pre- and post-rationalization. These new methods use interactive visual controls such as Euler elastica curves [40] or projected control curves [35,36] to constrain the initial design, ensuring its buildability while maintaining a modicum of design freedom. Others propose real-time physical solvers [14]. Finally, some methods focus on the efficient solving of linear or quadratic constraint equations to efficiently optimize paneling meshes [34,39,87]. We believe future research should be directed towards developing of real-time rationalization methods, which can be used during a parametric design process.

4.4. Machine-related fabrication constraints

We have shown that rationalization can be targeted towards different types of constraints related to design, construction, material, and machinery. Fig. 3 showed that the capabilities of fabrication machinery are the most commonly found targets for rationalization processes, appearing in 92 out of the 125 reviewed papers. These findings agree with previous statements by practitioners and researchers, who pointed out that architects must design for the capabilities of the fabrication equipment [135,136]. The findings highlight the importance of the concept of machinic morphospaces coined by Menges [63], which describes how virtual design spaces defined by specific machine related fabrication constraints can serve in form-finding methods.

In contrast, we have shown that most papers describing rationalization methods covered by this review focus on issues related to façade paneling such as mesh geometry. The focus on façade cladding is understandable due to its typically high price and overall importance to the perception of the building, and this area of research has advanced significantly over the last decade. However, the proliferation of CNC and robotic fabrication processes by the industry highlights the need to identify the machinery which will be used during the process of rationalizing the geometry. We think that future research should be directed towards finding rationalization methods specifically targeted at the capabilities of different digital fabrication machinery.

4.5. Concluding remarks

The idea that architecture is mostly an artistic or intellectual endeavor has fractured the relationship between architects and builders, a rift which has been expanding since the Renaissance [2]. Kolarevic noted that this relationship is experiencing a revival due to the rise of digital fabrication technologies and the technical capabilities architects must achieve in order to fully utilize them [137]. Our findings demonstrated the growing importance of rationalization in the field of digital fabrication and illustrated the different strategies available to architects for increasing their awareness and control over the fabrication quality of their designs.

The review highlighted the growing popularity of parametric co-rationalization strategies operating throughout the design sequence. We have shown that while these strategies are the most commonly used in the industry, the academia has not provided many applicable methods. Thus, we recommend that future research is directed towards developing easy to use parametric co-rationalization methods, especially ones which can operate in real time. As demonstrated by the findings, specific attention should be given to evaluating buildability in relation to the capabilities of fabrication machinery. These types of methods could function wherever rationalization is practiced: In the analytical evaluation of designs, in decision support methods such as expert systems and in the process of optimizing designs towards ease of fabrication.

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Appendix A. Supplementary data

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References
