Design-Built Rationalization Strategies and Applications
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Abstract
Rationalisation of architectural design is paramount to manufacturing and its construction. This paper presents a methodology of rationalisation of building envelope geometry. We discuss methods for understanding and addressing design complexity; review two theoretical models of rationalisation: the pre-rational and post-rational design principles; illustrate their benefits and limitations and demonstrate their meeting point proposing an integrated performance-oriented model for analysis and design of building envelopes, using digital design techniques.
1. INTRODUCTION

Rationalisation is a widely used term across disciplines such as the social sciences, mathematics, engineering and architecture [1]. We may categorize the broad range of available definitions into either (a) retrospective explanation of unconscious or ad-hoc behaviours via rational thinking or (b) prospective application of rational thought in establishing causal relationships. Rationalisation as an effort to systematize thinking and making seems to encompass both a notion of analysis as well as synthesis. Within the domain of architecture one may rationalise, or more precisely interpret, historical precedents to attribute sociocultural, economic and technological instigators for its inception and realisation. Rationalisation in the design-built process amounts to the effort of creating a structured methodology for translating a design from its conceptual phase to its end production while addressing the arising technical implications.

In this paper we study the rationalisation of a design process in two domains (a) strategies: we discuss the methods for structuring a design process and offer a sketch for a unified pre + post rational framework and (b) applications: we present an approach to address a particular family of rationalisation problems aiming to control dimensional component variance in contemporary digital design. The methodology used in both domains is based on architectural design-computation and the primary interface to design information is geometry. Both strategies and applications aim at simplifying or compressing a design’s information density optimising its geometry towards manufacturing and construction ends.

2. CONTEXT

Design rationalisation is not a new phenomenon but perhaps innate to the architectural design-built condition: Classical design media such as sketches and drawings express the desire of formalizing design and construction by figurative documentation in addition to information conveyed by natural language [1]. What is new today is the medium, namely design-computation. The emergence of a digital design paradigm occurred during the past few decades expanded the scope of design opportunity while it increased its complexity both formally and configurationally [2, 3]. Parametric models allow us to organize the design process using dynamic geometric and numerical relationships thus enhancing intuition by offering an opportunity to observe design considerations interacting with one another. Our digital models are not figurative or experiential representations of architecture but they compute design. The thought process used to compose design models is central in contemporary practice of design as they are the prime medium of explicitly expressing design intent. Within this context we focus our study on a computational version of design rationalisation as part of the process seeking to address complexity in contemporary design and provide the means of gaining insight, overview and control.
3. BACKGROUND

The principles of pre-rational and post-rational analysis and design are two prominent methodologies of architectural rationalisation in contemporary digital design. Their scope spans across the translation of concept design to detail development and eventually construction documentation. They have been extensively discussed by Shelden [4], Glymph [5], Whitehead [6], Hesselgren [7], Ceccato [8].

Pre-rational principles are based on layered application of logical rules, formalizing design as a process of interpolating composition of simple figurative and functional primitives: lines and arcs, quadratic and developable surfaces assembled using rule-based and associative modelling techniques. The International Terminal Waterloo Station (1993) and Eden Project (2001) by Nicholas Grimshaw and Partners; London City Hall (2002), 30 St.Mary Axe (2004) by Foster and Partners; offer some indicative examples of pre-rational processes where the design is strongly coupled with its generating constructive geometry principles which provisionally embed manufacturing and construction logic.

The post-rational perspective is rather an engineering systems approach to architectural rationalisation in that it is heavily based on analysis and optimisation processes using design-computation. An important assumption made is that design is an input which is retrospectively approximated to a rational tectonic model up to a notional design intent error tolerance. The Guggenheim Museum of Bilbao (1997) and Walt Disney Concert Hall (2003) by Ghery Partners; The Hungerburg Funicular (2006) and Heydar Aliyev Center (2012) by Zaha Hadid Architects, offer examples of design post-rationalisation where construction logic is fitted onto a rather more intuitively arrived at design expression.

While the distinction between pre and post rationalisation is a helpful formalization for the design-built process it is also artificial. We cannot assume that every post-rational process is preceded by an utterly unstructured design thinking process but merely one that is less explicit. In similar fashion we may picture a circumstance where pre-rational approach is employed as a form of reverse-engineering of an in-mind design concept which is also merely less explicit. Composite notions of rationalisation have been studied [9,10] as both means of resolving this dichotomy and mapping more realistically design rationalisation in practice which seldom employs one method or another. Insofar as extending the discussion we approach design-built rationalisation from a design rather than analytical perspective. Our inquiry is primarily focused on questions pertaining when a particular method seems appropriate and what are the implications in terms of process and product complexity. Characterisation may be seen as an attribution process identifying the load-balance between pre and post rational principles employed.
4. FRAMEWORK

Our framework identifies three design rationalisation components: (a) Description, (b) Analysis and (c) Optimisation. Those map onto the phases of generation, evaluation and selection within a design process. They are embodied within computer aided design modelling using for instance parametric or generative techniques; performance metric extraction using methods such as quantity, structural, and environmental computations; and finally automated design candidate filtering using artificial intelligence heuristics, numerical solvers and search techniques (Figure 1).

The framework is affine to classical models by Asimow [11] and Archer [12] however the reorder of events with design description, or synthesis, preceding analysis is used to allow for less explicit and exploratory design processes which may be formalized subsequently. Most importantly for contemporary rationalisation within digital media description, analysis and optimisation which are traditionally human operations, are assumed being embodied by computation or a composition between thereof. Finally, we allow these components to nest in one another in order to achieve complex design graphs.

Indicatively, we may employ the framework in a wide range of architectural and engineering applications such as tall building design [7, 13] where cladding unit configuration is computed using procedurally generated geometry while performance metrics such as wall cavity and floor areas are optimized via divide and conquer strategies. For the same building [14] present a structural engineering study where description is based on finite element modelling, structural analysis is used to evaluate the building performance and stochastic optimisation is employed to improve its static behaviour and reduce material use.

4.1. Design description

The concept of design description encompasses both visual and non-visual information which yields a design state. It is foundational for rationalisation as no analysis and optimisation can occur without it. Description aims at
establishing explicit relationships of generation and by implication capture the design intent. In architectural design, description is embodied in representations; a rather more computable version thereof is geometry. However, for engineering purposes the forces conveyed in material while may be visualized they are inherently non-visual design information.

While design description may provision for construction logic by embedding rules and constraints this is neither a prerequisite nor something to avoid. It is exactly this allowance that enables the same framework to express both pre and post-rational workflows. The more rules employed during the descriptive phase the more a particular implementation becomes pre-rationally conditioned and in effect proactively reduces its input and output domains. However we might as well establish a generative process that contains no prior bias and defers evaluation to metric analysis. In effect we may allow ourselves the freedom of a larger domain for design opportunity and in a consecutive step attempt to enforce reason from within or from outside the system’s description.

4.2. Design analysis

Metric analysis expresses design evaluation both quantitatively and qualitatively. Analysis looks at one or more performance criteria such as human, building and environmental factors. The notion of metric analysis acquires a form of design performance introspection within digital design as we inquire the descriptive model to report those metrics procedurally. Extraction of direct quantitative metrics such as lengths, areas and volumes is trivial given the analytical nature of computational geometry. However, complex or qualitative indicators require design and implementation of specialized analysis processes hence, design analysis becomes a domain of its own.

Pre-rational design contains integrated evaluation logic and it employs exactly those embedded criteria for generative purposes. However, it is not always possible to evaluate a design directly from its driving parameters; we still need additional external evaluation. Most importantly it is also beneficial to employ unbiased assessment processes disaggregated from the descriptive process as we may for instance catch logical mistakes and false assumptions. Post-rational design by definition places most of the work in this segment as it does not assume control over the generative description process.

While this segment is attributed as analysis it is essential to note that the selection, compilation and creation of design performance indicators from first principles or empirical studies is an act of art and design in as much a task of scientific analysis. Our case study demonstrates that even simple visual assessment criteria are very difficult to objectively classify and depend of personal or project specific goals.
4.3. Design optimisation

The notion of design optimisation is arguably the logical end to the availability of digital generative and analytical assessment systems. Its goal is to establish feedback loops and embody the notion of computer mediated decision making within design-computation. The scope of design optimisation may be localized and focus on narrow bands of the system or span across driving parameters and composite output metric indices. Optimisation may be as trivial as in generating a limited number of design options, characterizing them according to certain design criteria and selecting the most prominent, or it may be as complex as incorporating quasi or fully automated iterative search algorithms sampling vast domains before converging to a few design candidates.

Pre-rational design integrates optimisation logic to the extent that generation rules strategically target specific neighbourhoods of tested and proved solutions. Associative modelling using ruled-surfaces for instance proactively prunes a range of design possibilities exhibiting curvature characteristics that may not be as easily manufactured. However we may still use disjoint analysis and optimisation to break out of the tight boxes of pre-rational systems and explore the effect of complex design interactions that may not be easily modelled parametrically. Optimisation is absolutely necessary for post-rational systems as their descriptive domains are typically boarder and retro fitting directly implies an embedded notion of search.

5. APPLICATION

We will proceed with examining an application of the model via a case study of a computer aided design rationalisation of a complex building envelope. The particular design process is derived from an on-going project that cannot be disclosed at the point of publication upon client’s request. However the methods used are applicable to a wide range of free-form building envelope designs.

5.1. Description

The design intent is to create a curved wall in plan, and potentially in section, that may be simply generated and manufactured. We employ a pre-rational strategy of piece-wise tangent surfaces of revolution (Figure 2), also known as translational surfaces [5, 15], to define the cladding setting-out geometry. The result envelope belongs to a family of surfaces exhibiting certain desirable characteristics: (a) components are circular arcs which are simple to manufacture and geometrically offset without deterioration, (b) surface patches along the primary surface directions are planar quads thus suitable for curtain wall applications, and (c) the visual constraint of tangent continuity or apparent smoothness is ensured by definition.
In detail, we establish relationships between consecutive arcs such that at the transition points they share radial direction but not magnitude. A planar sectional profile may be then swept along the base path to generate the design surface. In addition, the section may be arbitrarily complex without violating the desired geometric properties.

The particular strategy has been presented in the past [5, 6, 15, 16]. Our implementation is a generalization of this technique using a smooth curve graph, or law curve, to produce continuously varying mesh geometries. Discontinuous graphs produce traditional piece-wise revolute surfaces while smooth graphs generate surfaces of pseudo-continuous curvature. Using the same principle we may also parameterize arc lengths, by additional graphs, to increase resolution at regions of higher curvature. Alternative pre-rational techniques using displacement graphs [17] can be used to mitigate numerical and formal shortcoming of radius-driven geometries while [18-20] offer in depth studies of planar quadrilateral meshes and developable surfaces from a post-rational perspective.

5.2. Analysis

Setting-out geometry typically spans large regions of a building’s envelope and it requires subdivision into smaller components which can be manufactured using standard industrial methods. Each arc is thus divided by a constant chord length into equal segments to pre-constraint the number of dimensionally unique parts (Figure 3). Control of the number of types is a logistical consideration as volumes of varying parts increase manufacturing and assembly time/cost and encumber the process of building information management on and off site.
Parts of large arc radius may be approximated by linear segments without visual distortion such that manufacturing costs of bending may be culled. There exists no objective threshold determining when the simplification is generally acceptable as the decision is bound to visual preferences, fabrication constraints and cost considerations. However, in principle shallow arcs of sagittal lengths measuring a few millimetres may be linearized with nominal errors (Figure 4).

We further observe that a chain of linear elements along an arc suggests that joints between segments require mitring at the bisecting angles, thus for each segment there is potentially a unique cutting pattern. Reducing manufacturing complexity implies averaging or squaring those angles such
that processing cost is reduced. The approximation induces a visual artefact known as the splay error where small gaps occur between consecutive segments (Figure 5). Again, there is no general consensus for when splay errors may be ignored or indeed introduces significant visual nuance. It is however common to ignore splay errors when they remain below typical architectural detailing and manufacturing tolerances. For example a few millimetres are within an acceptable range since even planar walls exhibit this dimensional range of detailing gaps at the joints.

5.3. Optimisation

The pre-rational system presented is geometrically predictable in indicating coarsely the number of unique elements required. We deduce that the number of unique segments (n) in plan times the number of unique segments in section (m) yields an upper bound of (n • m) total types. A composite cylindrical envelope independent of the number of patches requires one unit type, simple conic surfaces result to a number of types equal to the number of sectional segments and composites thereof require at most the product of patches times the number of sectional segments (Figure 6).

The aim of design optimisation in this case study is to answer the following design inquiry: Can we further reduce the total number of unique types and simplify the design and construction? This turns out to be a common problem, or a family of problems, where formal complexity results to dimensionally varying parts. Relevant previous work includes [9] attempting to rationalize the number of unique linear elements of a spatial frame; [21] study a similar problem from an engineering perspective such that by modifying the overall form and force distribution achieve using a
single cross sectional element in a bridge design; and [22, 23] identify typologies of curvature in fitting free-form envelopes with simple developable surfaces.

Our study was performed at a later phase of design development where there was no opportunity to modify the overall building form. Instead the rationale is based on the insight that the design contains variably sized parts which are variably spaced due to segmentation. Units and gaps between thereof lie at different building scales which hint of an opportunity to leverage part variance concentrating it into detailing voids instead of physical members. In particular, we focus at the transom carriers and attempt to reduce their length variance while allowing it to fluctuate in between.

**Description**

Variation control implies a notion of similarity classification where parts of certain closeness are averaged and refitted in the original design as long as they do not alter it dramatically. Our case study is a one-dimensional optimisation of linear member sizes thus we do not need to examine geometric affinity which is far more challenging. Identifying a fixed number of unique types which best approximate variation among a set of samples bound by an error metric is a data clustering problem. In particular it is an NP-hard problem addressed typically via numerical computation [24, 25].
Analysis

In order to understand the idea of variance concretely and measure the performance of our optimisation we need a benchmark strategy. We thus turn to statistics and use frequency histograms to record part size distributions and later compare clustering strategies. Cladding element sizes span the domain of real numbers which for complex envelopes every instance may be potentially unique. This is however a purely theoretical limit as manufacturing accuracies and construction tolerances allow us to define a discrete lower bound. For simplicity we define a pseudo-theoretical distribution increment of one millimetre, assuming this is the absolutely very least one may round unit sizes, and effectively count the number of non-empty histogram bins (Figure 7).

Generally we wish to perform better so we define a parametric increment bin-size of a few millimetres, round elements downwards to their nearest cluster, measure the average and maximum errors and count the number of non-empty or unique unit types. The maximum rounding error is bound by the cluster’s size, while the average error is approximately half of that. For 5mm bins we are certain that the worst rounding error will be strictly below 5mm while on average the error will be approximately 2.5mm. The process is computationally trivial as it may be computed using a standard spread sheet. Yet expectedly the results are suboptimal as by definition the histogram approach disregards all prior density characteristics of the distribution. By implication this means that we have no control over the end-effect of rationalisation as for instance gaps among units may
abruptly vary causing visual nuance. What we thus need is a strategy that may allow us to control how rounding errors present themselves in the final design expression.

**Optimisation**

For selecting better cluster pivots we developed a constrained k-means algorithm. K-means clustering is a statistical method for minimising intercluster variance [26, 27]. The algorithm selects a number of cluster partitions at random, associates each element with its closest cluster and repositions the partition centres at the mean of each cluster’s elements (Figure 8). The algorithm converges after a few iterations but it is sensitive towards the initial seed-cluster locations and requires repeated attempts.

Our application (Figure 9) uses a modified k-means method as we cannot allow units to increase dimensions upwards to their nearest cluster; elongated units may result to geometric clashes. Instead, we pin a cluster to the lowest bound of the range and skew the final cluster centres to their respective lowest bound. This subtle modification challenges the distance metric of the original algorithm. Intuitively it doubles its error as it coerces nodes from a clusters’ mid-point half way to its lower bound. We describe our method as two-times k-means strategy. Even so, the algorithm still performs on average 11% and 35% better than the benchmark in maximum and average errors. Moreover, k-means’ intercluster error minimization ensures that gaps will appear smooth within typology groups and only suddenly jump between clusters.

However, while k-means improves intercluster error it cannot address the problem of minimising the maximum error which is often visually more pronounced. A qualitative interpretation suggests that minimising the maximum error expresses the desire to control the largest visible gap change across an envelope while minimising the average error implies that small transitions need to be smooth. To minimise the maximum intercluster
error we employ the k-tMM strategy [28, 29]. The algorithm splits an initial cluster containing every envelope unit into sub-clusters while maintaining the min/max criterion (Figure 10). Eventually, each unit is rounded to the lowest bound of its cluster and the algorithm deterministically converges within two times the optimal [28]. Our implementation achieves on average 16% and 50% better than the benchmark strategy in terms of maximum and average errors, respectively.

Overall, we achieve improved results with both min/average and min/max compared to our initial benchmark (Figure 11). In terms of complexity k-tMM is simpler to implement, it runs faster; it is much more predictable and yields better results for large cluster sizes in both maximum and average errors perhaps due to k-means modifications which skewed what should have been a symmetric metric. Our parametric model produces the original design geometry as well as its end optimisation results at interactive speeds. Thus it is eases the process of design exploration and relays overall form refinement to the design actor by merging description, analysis and optimisation.
6. CONCLUSION

We presented a design-built rationalisation framework alongside a case study demonstrating how we may integrate pre and post rational principles to address the problem of high levels of part variation in formally complex designs. We conclude by offering observations on the thinking process of rationalisation systems within digital media.

The question we propose as per when or how one may select a pre or post rational approach to rationalisation cannot be seen as an either/or proposition. Instead we may use a set of indicators to assist and guide the decision making process. Pre-rational principles offer a visual paradigm for expressing design information via primarily associative geometric modelling technique. Component/configuration organizational principles allow pre-rational modelling to achieve complex design compositions. We attribute this notion as systemic compactness whereby simple operations yield expressively complex results. Interestingly this behaviour is achieved while ensuring certain upper bounds in terms of complexity expectation. In our case study we can predict coarsely the expected part variance already from input parameters generating the design surface. Sensitivity-wise pre-rational models behave also fairly linear towards small parametric variations. We attribute this notion as systemic predictability, which is the degree we can foresee how generative actions effect results.

The rules captured by pre-rational systems are usually simple and may be replicated with limited or no computation using traditional media. Revolute building envelopes may be inefficiently drawn by hand because intrinsically they involve merely affine geometric transformations. Pre-rational methods in this respect are somewhat calculation averse. Simplicity at the descriptive level though maps naturally to conventional design.
processes and allows design teams of various degrees of comfort with computation to engage and contribute. For instance cladding setting-out geometry is used for space planning, structural steel layout, quantity surveys etc. The ability for multiple parties to operate, evaluate and verify the design at the same level of information complexity defines a notion systemic reliability: it is possible to manually reproduce, gracefully decompose, easily verify and communicate the products of a system.

While descriptive elegance and simplicity, intuitive capability for provision and insight, as well as procedural and output dependability are certainly appealing properties of pre-rational systems there are also expressive and technical shortcomings. The computation averse and visual oriented attributes of pre-rational systems limit expression and problem solving from exploiting powerful capabilities within digital media. Simulated form-finding and discrete computational geometry for instance do not fit well in these models. Meanwhile, the deterministic directed acyclic graphs constructed using pre-rational methods tend to fall short answering fairly simply stated design inquiries which typically involve implicit or inverse relationship interrogation [30].

Our post-rational sub-system within the optimisation study also exhibits similar systemic properties. Descriptively we formalized our problem by transposing the inquiry into the domain of statistics and data clustering. The process of transforming geometric information into numerical, operating on it using methods from domains of knowledge which are not traditionally appear relevant to architectural design and eventually translate information back to a formal domain in order to assess the implication is fascinating. Moreover, in order to understand complexity we may refer to concepts from information theory such as entropy, asymptotic analysis, NP-hardness etc. These are very precise and powerful tools compared to observational assessments of worst case scenarios. In addition, implementing optimization algorithms, understanding and communicating their results and operating on numerically optimized models are processes which are fairly foreign to architectural design and we will need long term exposure and experience before we can naturally integrate in practice.

As contemporary design praxis in architecture, engineering and the construction industry is rapidly transforming by the introduction of design information technologies we find ourselves creating highly sophisticated building information models which we modestly use to leverage tasks such as document control, trades coordination and the assessment of basic building metrics such as quantity surveys and clash detection. Our study suggests for an expanded paradigm of this process where we may no longer rely only on prefabricated systems of smart parametric objects but embed functional components of description, analysis and optimisation to take advantage of the power within design information and address the challenging issues arising during the translation of concept design to construction.
Design computation has flourished over the past decades with main focus of research placed on exploratory design studies and the development of primarily descriptive systems. Metric analysis and design optimisation are still relatively nascent at least within the realm of architecture. Analytical methods for engineering such as the finite elements, the fluid dynamics and a range of environmental evaluation techniques are far more developed. In architecture, there is a great opportunity to invent design metrics capturing qualitative aspects of design such as spatial and visual performance for instance. This requires a certain mental leap from the notion of representations to design information we can analyse and compute with. We have been using photorealistic visualization technologies for the longest time for example but we rarely appreciate those tools for their analytical and predictive potential for they employ equally highly sophisticated probabilistic light simulation techniques. Design optimisation holds also great research potential not merely for resolving intractable design relationships which we cannot possibly model by associative principles but also to assist us identify unexpected and surprising design possibilities lying beyond human intuition. In summary, the goal of the description-analysis-optimisation model is not to remove and replace the design actor by computation but to expand the information processing capability and increase design information density.

With respect to the adoption of digital fabrication technologies for part manufacturing and potentially the construction, we note that rationalization is not contrary but complementary to the process. The downstream demand for highly precise manufacturing information to drive numerically controlled machinery will raise the expectations for procedural generation and processing capability of upstream design information. Information analysis, filtering, classification as well as concepts such as simplification and compression will have to readily change orientation from catering capabilities and limitation of conventional industrial mass production to large scale bespoke manufacture.

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REFERENCES


26. MacQueen, J. B., Some Methods for Classification and Analysis of Multivariate


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