# Axiomatic Design facilitating integrated building design and operation.

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**Abstract.** The paper presents an initial reflection on the possibility of adopting Suh's Axiomatic Design (AD) as a framework to integrate and coordinate the different methods used by the Architecture Engineering and Construction (AEC) industry to evidence-base decision-making for sustainability. A taxonomy for aggregating the different methods used by the AEC industry is proposed so they can be inserted into the AD framework and used to support and formulate evidence-based design decisions in a way that is systematic, informed and, among other things, traceable so true records of the design process can be retrieved. The taxonomy is based on the new EN ISO standards and the literature on design research and decision-making. It organizes the discussion about the feasibility of having AD as a facilitator for integrated building design and operation in the AEC industry. Three potential issues are identified from this proposition, which call for further research and academic debate in the AEC and AD communities, laying the conditions for fruitful future interactions between them. On the one hand, the paper proposes that the AEC community can consider AD as a catalyzer to promote integrated design for sustainability. On the other hand, it pushes AD to be adapted to accommodate the needs of a fragmented design industry which often produces one-off design solutions.

**Keywords:** AEC industry, Design for sustainability, Integrated design, Axiomatic Design.

## 1 The fragmented AEC design for sustainability process

This paper examines a proposition for integrating Suh's Axiomatic Design (AD) with common methods used by the Architecture, Engineering and Construction (AEC) industry, providing a methodological and theoretical framework to support integrated design for enhancing sustainability-oriented design decision-making processes. Integrated design, in this context, refers to a reconciliation of methods, decisions and solutions from different specialisms towards providing a single and comprehensive material response to complex, potentially conflicting, and interwoven requirements, considering the whole life cycle of a building – from conception to operation, re-use, demolition and recycling.

Design for sustainability in the AEC industry has to address multiple types of stakeholders' needs, deals with large amounts of multi-domain information, and should be evidence-based to show solutions proposed work effectively (prior to and after an asset is built) while being heavily regulated and permeated by liabilities. This is particularly the case in projects that wish to apply for sustainability certification by, for instance, the Living Building Challenge (LBC) [1], which has clear requirements to achieve living within planetary boundaries. These standards have requirements which, to be fulfilled, need cross-disciplinary interactions and concerted action throughout the design process; e.g., relying solely on solar power for energy supply balancing demand accordingly; integrating renewable energy systems with electric vehicles on-site; maintaining a balance between water supply and demand through rainwater harvesting; using materials that are renewable, recyclable and do not release volatile organic components which can compromise the health of building occupants. In these types of projects, successfully coordinating the AEC design process for integrated design to achieve sustainability-related design requirements is not a trivial task. It involves coordinating the design delivery process from multiple aspects including stage outcomes, core tasks, core statutory processes, procurement routes and information exchanges among the design teams [2] to achieve design solutions that outperform current building industry standards; while protecting professionals from unforeseen and uncommon liabilities. This is particularly relevant because over the last few decades, technology and specialization have created a disconnect in design decision-making, reducing opportunities for integrated and innovative propositions.

In general, architects adopt solution-focused approaches to ill-defined design problems, and the process follows a spiral, cyclic structure. On the other hand, engineers apply problem-oriented strategies to well-defined design problems and the design process is implemented through a linear sequence of activities [3]. Architects normally rely on precedence and repertoire to make complex decisions whereas experts, and engineers tend to work in silos with domain-specific computational models designed to perform specific activities, but not integrated into a coherent procedural framework [4]. Precedence, repertoire, and modelling approaches of the physical world, which share common design parameters but are developed to achieve different performance objectives, do not enable decisions to be integrated. Rather, many times they push conflicts to be reconciled through Decision Support Systems which are highly deterministic (e.g., multicriteria analysis, optimization, etc.).

In practice, approaches such as the Integrated Design Process (IDP), attempt to support sustainable building design and construction with strategies for project teams to share a vision of sustainability and work collaboratively to implement goals at appropriate design phases during the project development process [5], [6]. IDP seems to successfully describe generic management procedures outlining guidance on roles, tasks, and critical activities during each stage of the process [7]. It complements conventional project management approaches but falls short in support of coordinating integrated decision-making within multidisciplinary design teams [7].

Some authors in the literature [8], [9] suggested the re-integration of the architects' and engineers' models into a common procedural framework suitable for both disciplines to support design teams in transdisciplinary collaboration. According to [8], a common model of the design process should reproduce the process of going to-and-from problem and solution, and sub-problems and sub-solutions. In this process, problem definition should depend upon solution conjectures which, in turn, help clarify the design problem. The latter should be hierarchically decomposed into sub-problems, while the overall design solution should be developed by generating, combining, evaluating, and choosing sub-solutions which respond to different sub-problems. On the basis of these premises, Suh's Axiomatic Design (AD) has been proposed as an appropriate common approach for supporting architects and engineers in performing decision-making in conceptual building design and modular design [10]–[12], but a common model able to integrate, into the design process for sustainability, the multiple methods used by different AEC design disciplines to make decisions is still missing.

The lack of an integrated design decision-making framework in both design practice and research poses a challenge in producing truly sustainable solutions. Key performance indicators (KPIs) alone are not sufficient to produce sustainable design, especially when they need to be achieved through manipulating design parameters that are common to different knowledge domains. KPIs, in which liabilities are higher or KPIs which are connected to higher profits, tend to be achieved, many times to the detriment of KPIs which promote health, wellbeing and/or other environmental gains. Relationships between KPIs and design parameters common to many knowledge domains have to be coordinated through concerted action so design solutions can achieve multiple requirements [13]. The AEC industry does not have a framework to specifically support this coordination; it does not have a framework to support the generation of design solutions which respond to requirements from multiple domains, particularly those which are difficult to measure and/or to cost but promote health, wellbeing and/or other environmental gains.

***This paper conjectures that AD could help coordinate the different stakeholders' needs, design, decision-making, and project control methods used by the AEC industry to achieve integrated building design and operation. In this way solutions may better address the different sustainability goals of the 21st century.***

The paper starts by proposing a place for AD in the AEC industry. It then groups common methods used by the AEC industry to extract stakeholders' needs, make design proposals, decide upon and test design alternatives, including methods which control the performance of the end product when designing for sustainability. It finishes by discussing the position of these methods within the AD approach highlighting fits and misfits with AD components (e.g., applied principles, axioms etc.), outlining areas for deeper investigation and future joint AEC and AD development.

## 2 Proposing a place for AD in the AEC industry

Disagreement in approach between architects and engineers in practice can complicate collaboration particularly in relation to "how design decisions are balanced to achieve overarching project targets, negotiated among project team members, propagated into the information flow of the design process, and subsequently revised as the project develops” [14]. Information management systems and the increased specialisation and automation of the construction industry call for project coordination to happen in a systematic way with a clear push for the entire process to be traced, with true records to be put in place so the diversity of liabilities behind them can be monitored.

AD enables the co-evolution between problem and solution to be traceable, and the decision-making informed, while facilitating knowledge and information transfer, storage, and retrieval as well as enabling the engagement and coordination of multiple stakeholders. Moreover, AD provides a sequence of stages and activities to progress the project (AD domains) and a sequenced creation process based on going to-and-from problem and solution, plus to-and-from sub-problems and sub-solutions (zigzagging). In AD, problem and solution are systematically and consistently specified in parallel, moving down a hierarchy, and design decisions are made in an explicit way, maintaining data. AD is supported by general decision-making principles (Suh’s axioms, corollaries, and theorems) which help define effective designs with respect to specified requirements, evaluate the synthesized ideas, and select the most feasible solution among valuable alternatives [15], [16].

AD has been applied to sustainability issues in designing manufacturing systems using constraints to avoid undesirable outcomes while enhancing creativity to enlarge solution spaces [17]. Suh’s axioms guide the selection between candidate design solutions. However, AD is somewhat silent on the generation of candidate solutions. Moreover, a constraint-based approach to design for sustainability can result in diminished solution spaces and over constrained problems, but this can be addressed fostering creativity enhancement in design processes [17].

While the AD approach may be suitable to support an integrated design process, it is important to assess how it can accommodate current AEC methods used in design. These AEC methods include identifying and mapping stakeholders needs, supporting decision-making by proving designs attend to these multiple needs, as well as controlling the delivery process towards fulfilling them as best as possible. To the best of the authors’ knowledge, there are no records of how these different methods can be integrated through AD, neither is there a taxonomy that enables their integration within an overarching framework to be properly coordinated and assessed as the design process progresses.

Figure 1 shows where the most common methods used by the AEC industry to design and how they can potentially be integrated via AD, together with a taxonomy used to aggregate these methods into four different groups namely ‘Briefing Methods’, ‘Design Methods’, ‘Decision Support Methods’ and ‘Project Control Methods. The taxonomy was put together combining recommendations from the EN ISO 19650 series, which refer to information and asset management, together with the literatures in design research and decision-making in engineering. The rationale behind each group is presented in section 3, whereas a discussion about how each group of methods can potentially fit within the AD framework is presented in section 4.

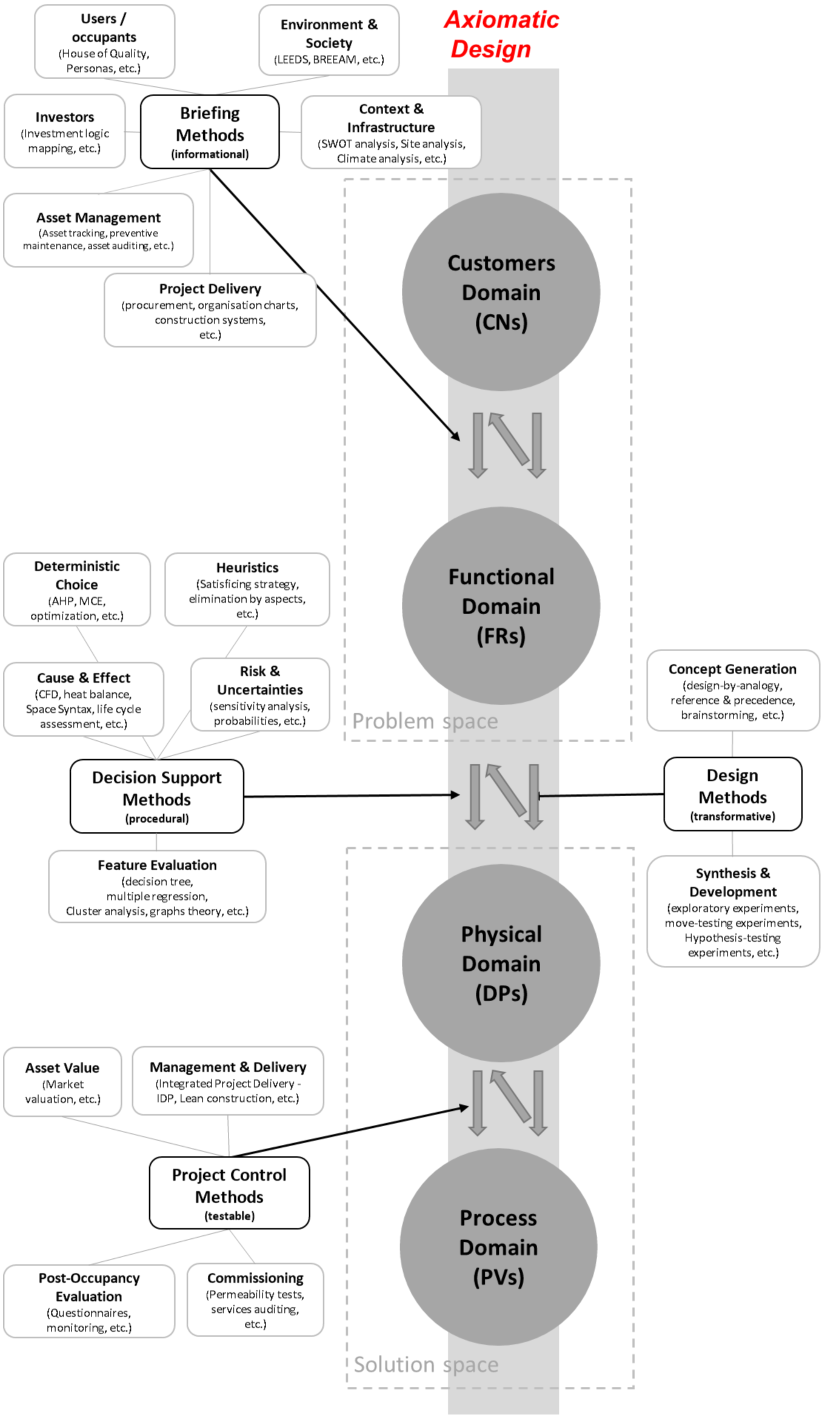

**Fig. 1.** Placing methods to design for sustainability used by the AEC industry in AD.

# 3 Methods used to design for sustainability in the AEC industry

Methods and information management systems are operational for designers to design. They are part of the ‘systems of knowing in practice’ [18] and are important elements of design practice. They are more informative than design inputs and outputs (as proposed by [19]) to understand decision-making and enable decision chains to be recorded, while at the same time inferring the potential decision-makers behind them. Records of this type aid project coordination and provide evidence of correct attribution of responsibilities and liabilities, which permeate the AEC industry, while also enabling knowledge transfer within and across the different disciplines involved in the design process.

Briefing methods, design methods and project control methods reflect the employment of tacit knowledge in solving design problems, while decision support methods and information management systems make designers’ ontologies and epistemologies explicit, facilitating scrutiny when prioritizing, coordinating and reconciling decisions.

Briefing methods are informational and therefore used to collect information to specify design requirements and constraints. Design methods are transformative, moving from what a situation is to what a situation will be, and used in the co-generation of problems and solutions. Project control methods are testable and used to keep in check the different aspects related to product development process and performance in use. Decision support methods are procedural as they contain clear procedures to aid in decision-making. Transversal to all these methods, and hence falling out of the scope of the discussion on AEC methods’ integration in AD, are information management systems: ontological and relational, enabling different types of project information to be tracked throughout the whole design process.

## 3.1 Briefing Methods

Briefing methods were classified by type of information needed to formulate design problems based on the different information management perspectives presented by EN ISO 19650-1 [20]. They depend on the needs and aspirations of different stakeholders who are part of the design process as well as on the needs, opportunities and constraints imposed by the context in which the design will be inserted, from site to society.

The sub-category ‘Users/ occupants’ groups methods is used to identify needs and aspirations of building users/occupants to ensure the design solution satisfactorily responds to them. This sub-category is well known to the Axiomatic Design community, and it contains methods commonly used in marketing (e.g., House of Quality) and in human-computer interaction (e.g., personas), to cite a few.

The sub-category ‘Investors’ groups methods used to identify the needs and aspirations of project clients, who might not necessarily be the occupants or users of an asset but have clear financial targets for it. Methods commonly used to map investors’ needs and aspirations come from the business domain (e.g., investment logic mapping).

The sub-category ‘Asset management’ is a particular category in the AEC industry with specific needs for the operational phase of an asset (the longest phase in any asset life cycle). Methods commonly used to map asset management needs come from maintenance engineering, building controls and operation (e.g., preventive maintenance, asset auditing, asset tracking) and are potentially alien to the AD community which mainly deals with the asset up to the end of its production life.

The sub-category ‘Project delivery’ groups methods predominantly used to extract needs related to the coordination of the different parts of a project supply chain, so they are satisfactorily completed and delivered to clients. They include project management, construction, and procurement methods (e.g., procurement routes, organization charts, construction assemblage systems) and deal with specific needs affecting project requirements from the beginning, many of which cannot be changed after planning application or analogous project milestones.

The sub-category ‘Context & infrastructure’ is particular to the AEC industry as it focuses on methods to extract needs, opportunities, and constraints of the context an asset will be inserted in, more specifically its site, climate, neighborhood, and its social and environmental ecosystems. Methods used in this subcategory come from architecture (e.g., site analysis), planning (e.g., SWOT analysis) and building physics (e.g., climate analysis) and provide usually unique information to design a ‘prototype of one’ as every building is a one-off custom job with little economy of scale or customized information to design modular solutions.

The sub-category ‘Environment & society’ focuses on methods used to extract wider societal and environmental needs of a project which are normally prescribed by, for instance, building sustainability standards (e.g., LEED, BREEAM). These methods ensure needs are set based on collective interests, rather than individual ones from clients and users/occupants alone.

### 3.2 Design Methods

Design methods were classified based on the type of transformation they enable by merging the reflective practice approach proposed by Schon [18] with the disintegrated design process proposed by Jones [19].

Therefore, ‘Concept generation’ methods resemble what Jones [19] describes as “methods of searching for ideas”. They reflect the more intuitive part of the design process in which searches for potential design solutions are undertaken to select a subset, or one of them, to be further tested and developed. Methods used in this sub-category come from engineering design (e.g., design-by-analogy), architecture (e.g., reference or precedence search) or both (e.g., brainstorming).

On the other hand, ‘Synthesis & development’ methods resemble what Schon [18] describes as “design experiments in a wider sense”, i.e., not only including Schon’s experiments but any other potential types of experiments which enable design ideas to be synthesized and further developed. Design experiments proposed by Schon are fundamentally different from Jones’s transformation methods. The former expresses what designers want to achieve out of the experiments they propose, whereas the latter is a collection of different procedures to connect problem and solution spaces. Thus, methods in this sub-category comprise the three classic experiments proposed by Schon [18] (exploratory experiments, move-testing experiments and hypothesis-test experiments) but can be extended to include digitally assisted design experiments, which connect synthesis and development with decision support systems (e.g., parametric design methods, digital fabrication methods, etc.).

### 3.3 Decision Support Methods

Decision support methods were grouped based on the type of evaluation they enable designers to use when making decisions. These can vary from rational decision-making [21] to decision analysis [22] up to heuristic [22]–[24] methods.

Rational decision-making methods assume there are optimal design solutions and/or the best choice among design alternatives [21]. Methods of this sort provide value judgement about the desirability of a design and were grouped under the sub-category 'Deterministic choice' methods. They are commonly applied to detailed building design stages (optimization, multi-criteria evaluation, etc.) to, for instance, fine-tune design decisions about building materials, service components, etc. They have gradually been pushed to be implemented in early design stages to optimize building energy performance as a means to rationalize decisions related to, e.g., façade components and construction systems [25].

'Decision analysis methods' are decision support methods which enable designers to identify, represent and assess decisions to be made [22]. They are tools for decision analysis and can be categorized under four different sub-groups; 'Cause & effect', 'Feature evaluation' and 'Risks & Uncertainties'.

The sub-category 'Cause & Effect' is widely used to inform performance-based building design through the application of, for instance, building physics models and simulations of different sorts (e.g., heat balance, computational fluid dynamics, pollution dispersion, etc.). Methods of this sort are used to predict the behavior and performance of different design alternatives and can be used in isolation, to describe the consequences of different design decisions, or in combination with other decision analysis and/or rational decision-making methods when judgments need to be made.

The sub-category 'Feature Evaluation' groups methods predominantly used to extract information from data through machine learning algorithms of different types (e.g., decision trees, multiple regression, cluster analysis, etc.). Methods in this category are used to identify characteristics between different design variables such as window and balcony size, which influence daylight performance [26] by post-processing building simulation results.

The sub-category 'Risk & Uncertainties' groups methods used to undertake systematic data analysis based on mathematical models developed to assess how variations in design parameters affect design solutions. Methods of this type are widely used with building performance simulation (e.g., sensitivity analysis, risk assessment, robustness, etc.), to assess for instance, how uncertainty in relation to material properties affects building performance [27]. Recent experimental research can also be found in [28] who proposes a methodology which integrates robustness and risk assessment examining decisions made at the early design stages considering reversal in ranks, delayed discovery and insufficient gain or loss of performance gains.

The sub-category 'Heuristics' comprises groups of methods applied when decisions need to be made under uncertainty [22], when intuitive judgement is needed [23], when multiple alternatives are available [24], etc. basically when a choice needs to be made in the absence of a deterministic method. This is a commonly used method in the AEC industry. It can be found, for instance, in early design stages when deciding to proceed with a specific design hypothesis if it satisfies a basic aspiration level (e.g., satisficing strategy). And it can also be found during design development when the number of candidate solutions is reduced by eliminating one-by-one alternatives that do not meet certain aspirational levels (e.g., elimination heuristics).

### 3.4 Project Control Methods

Project control methods, providing feedback on whether the purpose of the different stakeholders' needs and aspirations for the product are met, were classified by their testing objective. To this end, they reflect the purposes for an asset listed according to different stakeholders' perspectives in ISO 19650-1 [20]. However, their sub-categories were mainly defined based on the Soft-Landings Approach [29], which focuses on asset operational performance and meeting of client's expectations.

The sub-category 'Asset value' groups methods related to assessing the value of the asset to its investors and/or owners. It is a particular sub-category of the building sector as "buildings [are] financial assets that figure in forms of market exchange…" [30] and therefore need to fulfill specific investors/owners needs related to strategic business cases for ownership and operation [20]. Methods in this category come from business finance and operation (e.g., Market valuation, etc.) and are used to gauge the value of the asset to investors throughout project development up to buildings in operation.

Since all stakeholders have aspirations for the asset behavior and performance, the sub-category 'Post-Occupancy Evaluation' groups methods that deal with asset performance in operation. It groups the methods used to assess building performance in use, i.e., while the building is already being occupied [31]. It includes user/occupant satisfaction, building and energy use, providing feedback on how well the asset is fulfilling users/occupants needs while in use as well as how well the asset is responding to contextual, infrastructural, societal, and environmental requirements. Post-occupancy evaluation methods come from Psychology, Social Sciences and Economics (e.g., questionnaires, interviews, etc.) when referring to user/occupants' satisfaction, and from Engineering (e.g., monitoring, etc.) when referring to asset and energy use.

The sub-category 'Commissioning', on the other hand, deals with building response and functioning right after construction, when a series of procedures are undertaken to test, check and ensure the building and its services are operating as designed. Methods in this category come from different Engineering domains (e.g., permeability tests, services' auditing, etc.) and form part of a mandatory building delivery stage in many countries [2].

The sub-category 'Management & Delivery' refers to methods employed to control the whole project organization and delivery, from design to manufacturing and construction of an asset up to its handover to the client. Specific needs for this category are included in the project brief and followed throughout the life of a project using different types of project management methods. Examples of project management methods applied to sustainability include Integrated Project Delivery (IPD) and Lean Construction, which respectively focus on the development of sustainable integrated project solutions and construction waste reduction.

### 3.5 Information management systems

Contrarily to methods, information management systems were not classified and inserted into the classic AD framework [15], [16]. They are a standalone group mentioned in this section only to highlight that the AEC industry uses a collection of complementary models, databases, and schemas to represent assets and record associated information. These models and schemas collect information throughout the design process using different ontologies and epistemologies, not always reconciled through interoperable software features. For instance, Building Information Management Systems [32] are structured to represent asset construction properties and the relationships between them, whereas metadata schemas such as Brick or Haystack are structured to represent buildings in operation, mainly the operation of their services and controls [33].

## 4 Can AD coordinate integrated AEC sustainability projects?

An outline on how different AEC methods to design for sustainability can be integrated via AD has been proposed in Figure 1. This outline acknowledges that problem and solution are progressively specified, starting from an analysis of needs, and moving to the generation of possible solutions through an iterative process of zigzagging between the problem (what) and solution (how) spaces, including Process Domain [34]. Prior to any empirical testing it is already possible to highlight some conceptual issues in the proposed framework, which emerge from misalignments between how AD was developed and is supposed to be applied in product design, and the current AEC design practice.

The first issue refers to how far one can go with zigzagging in the AEC design practice. Delivery methods in the AEC industry are structured based on a complex system in which contracts, procurement and core statutory processes are interwoven. Clear design stages are put in place for projects to be developed so professional services, information exchange and contracts are prepared accordingly (e.g., [2]). These stages contain not only milestones for client approval but also milestones for core statutory process approvals (e.g., for the UK are specifically planning, building regulations and health and safety approvals). Statutory processes of this type imply freezing solutions as submitted since only minor changes can happen after approval. This means zigzagging is *de facto* restricted between core statutory process approval points throughout the design process and design delivery stages, contractually used to set up milestones for client’s approval.

Acknowledging this limitation and attempting to better bridge issues appearing in the early design stages with issues related to construction and operation, delivery processes have been amended to include Soft-Landing principles [2], [29]. However, much is still to be done with regards to how Soft-Landing principles can be made operational as the implementation of these principles mostly depends on the existence of a consistent framework for their integration throughout the design process. AD can be extremely helpful in this front if it integrates AEC briefing methods in the zigzag happening between the Customers and Functional Domains. This is particularly the case if ‘Asset management’ and ‘Project delivery’ methods are brought to the early design stages and integrated with ‘Investors’ and ‘users/occupants’ methods to better inform the definition of Functional Requirements (FRs). FRs are the functions that must be fulfilled by the physical elements, Design Parameters (DPs), in order to satisfy customer and stakeholder needs [15]. AD can also be extremely helpful if it integrates ‘Project delivery’ methods in the zigzag happening between the Functional, Physical and Process Domains filling a particular gap essential in designing for sustainability [2]; the one of considering Process Variables (PVs), the variables involved in producing the specified DPs [15], in form generation. According to Frampton [35], the architectural form/shape is the result of “the constantly evolving interplay of three converging vectors, the *topos*, the *typos*, and the *tectonic*” [35] where the term “tectonics” encompasses the construction process from the materials up to the finished building [35], [36].

Interestingly, integrating these methods to the AD approach addresses some of the flaws highlighted by [37] in the AD literature. Specifically, ‘Briefing methods’, as defined in this paper, address issues with regards to identifying the key stakeholders involved in the design process, which for the AEC industry are clearly listed in the [20]. These same briefing methods are also powerful to identify different stakeholders’ needs enabling them to be mapped and specified separately, to ensure that all aspects of the problem are properly defined and addressed [38] as the project progresses.

On the other hand, the mapping of stakeholders’ needs to functional requirements and constraints as described in AD is not a straightforward task. AD – in its purest form – does not offer adequate instruments to capture the variety of requirements that the AEC design process has to master, with consequent problems in the design specification phase and in the application of axioms 1 and 2. To this end, the classification proposed by Thompson [37], [38] may supplement the framework proposed in this paper by providing clear strategies to identify constraints and non-FRs: both common elements in the AEC design process and requiring special consideration with regards to decision-making methods used to address and assess them.

Because AD is not prescriptive with regards to design methods to be used throughout the design process, the variety of methods employed by the AEC industry to deal with ‘Concept generation’ can be seamlessly integrated in the presented integrating framework. ‘Synthesis & development’ methods proposed in section 3 can be used to augment AD design matrixes, relating DPs and FRs, with matrices relating DPs to DPs. Design matrices alone do not support specification of interactions between physical components (DPs) for the physical integration of system elements into a whole-design solution. This is particularly the case because ‘Synthesis & development’ methods are centered in design experiments having holistic assessment goals. Therefore, easily admitting the introduction of, for instance, Design Structure Matrix (DSM) [39], [40] or Interaction Matrixes [19] which represent how each element in the overall system relates to every other element in the system. Such matrices relating DPs to each other are used to assure that physical integration does not violate Suh’s Axiom 1, maintaining independence of the FRs [41]. In this context, combining AD and DSM, for instance, can well be used to assess the implementation of sustainability requirements such as reusing, repairing, and remanufacturing towards resource circularity. Recent applications show an initial effort to use AD and DSM in construction projects for better control on changes [42].

A second conceptual issue, however, can be identified when attempting to integrate 'Decision support methods' to AD. On one side, the authors acknowledge that the AD approach already provides designers with two principles, Suh's Axioms 1 and 2, independence and information axioms, to support decision making in order to define effective designs with respect to specified requirements, to evaluate the synthetized ideas and to select the most feasible solution among valuable alternatives. One the other side, it could be said that Suh's Axiom 2, minimize the information content, does not admit 'Deterministic choice' methods because value judgement should never be deterministic. This, in principle, prevents such methods from being implemented in any design stage, despite these clearly gaining traction in the AEC industry. Whilst 'Deterministic choice' methods can be unsuitable if used in the early design stages as they freeze solutions rather early in the process, their potential to assist decision-making in detailed design stages can accelerate choice (e.g., use of multi-criteria evaluation or optimization routines in façade design to integrate construction and energy performance). Thus, the case for using Suh's Axiom 2 in AEC projects should be further examined.

Moreover, Axiom 2 prescribes the use of a specific decision analysis method, namely boundary searching [19], in which limits to acceptable solutions are specified based on probabilities of DPs fulfilling FRs. This prescription leaves room for multiple 'Cause & effect' methods to be applied to assess the success of manipulating different DPs towards achieving specified FRs. However, it excludes the application of some 'Risk & uncertainties' as well as 'Feature evaluation' methods. Despite not being prescriptive about how probabilities are calculated, boundary searching determines how probability results should be assessed, ruling out methods such as decision trees (part of the 'Feature evaluation' group), and expected relative performance losses (part of the 'Risk & uncertainties' group), to cite a few.

Axiom 2 also limits the use of 'Heuristics', including formal methods of heuristics, by not admitting, among others, the use of Satisficing Strategy and Recognition Heuristics, whilst promoting Elimination by Aspect [24]. Limitations in the use of 'Heuristics' can be a problem when assessing non-FRs and constraints as these many times do not have an associated probability function and therefore require 'softer' methods of assessment, such as for instance Simon's Satisficing Strategy. Relaxing the use of Axiom 2 would potentially increase the range of admissible decision analysis methods. However, more work is needed to understand, in detail, how each different decision-making method can be used if AD becomes the main decision-making framework used by the AEC industry to promote integrated design. Also, more work is needed to determine how this collection of methods complements the AD decision-making framework so it can better respond to the particularities of different design domains.

As part of this examination consider that Axiom 2, on minimizing information, should be applied after Axiom 1. That is, the best design solution (DP) is the one among those candidates that maintains the independence of the FRs equally well (Axiom 1), that has the least information content [14]. Axiom 2 ranks the candidate solutions that satisfy Axiom 1. Information content is defined as the log of the reciprocal of the probability of success in fulfilling FRs and avoiding constraints, therefore minimizing the information content (Axiom 2) is equivalent to maximizing probabilities of success. There can be important uncertainties in determining probabilities of success, hence uncertainty in these Axiom 2 based rankings. Considering Axiom 2 secondarily, however, limits the need for its applications and the associated difficulties.

The third conceptual issue arises from a set of particularities of the AEC design process which make assessing the success of a design solution a substantially difficult task. Every building is unique, not possible to be prototyped, and has to respond to the needs of multiple stakeholders with different goals and involved in different stages of the process.

Buildings have to respond to a specific site, climate, client, and occupant needs. Whereas standard solutions can be deployed in different parts of the design process (e.g., construction pre-fabrication, etc.), the combined response is always an idiosyncratic, large, and expensive intervention which cannot be tested through prototyping. There is no possibility for zigzagging to be implemented until the best version of a product can be developed. Therefore, testing the response of a building in its fullness can only be done after the building is built. This means only Project Control methods related to ‘asset value’ and ‘management & delivery’ can be used in the design stage, but these primarily respond to the needs of the investors and the project team. Methods such as ‘Commissioning’ can only be applied at the end of the construction phase as they specifically check if the building and its services are operating as designed. ‘Post Occupancy Evaluation’ methods, can only be assessed for building already in operation as they depend on how user/occupants interact with the building while it is managed.

The absence of prototyping makes the predictability of success highly dependent on decision-making methods used throughout the design process. These methods have to factor in uncertainties related to use and operation combined with climate related uncertainties. After all, building performance will depend on how the occupants interact with the building as well as how the building responds to climatic variations. As a result, there are large investments in research and practice towards developing decision-making methods related to predicting these uncertainties (IEA annex 79).

Initial attempts to record occupant-centric design patterns to inform design have been made in [14]. These patterns contain records of the application of different ‘Cause & effect’ methods to assess buildings’ environmental performance together with ‘Risk & uncertainty’ methods related to occupant behavior, for facilitating the use of both in coordination when assessing design proposals. Whereas this proposal does not fully cover for uncertainties in relation to building usage in general, but mainly energy usage, it enables user behavior to be directly factored in the EAC design process, thus enabling performance to be assessed by applying Axiom 2. Occupant centric design patterns can be used also to simulate design robustness to different types of occupancy behavior, pushing the use of control methods to the zigzagging between the Functional and Physical domains. However, these are yet to be tested in practice so they can be expanded to include further aspects of performance testing, among which user/occupants’ satisfaction. These call for further research, potentially between the Annex 79 and AD communities.

## 5 Conclusions: Adapting AD to the AEC community needs

This paper presents the initial results of an attempt to use AD to coordinate and integrate, in orderly fashion, many methods used to support evidence-based design in the AEC industry to produce design solutions which respond to current sustainability challenges. In theory, using AD to this end would not necessarily clash with the way the AEC industry currently operates. On the contrary, AD could promote the integration of many of these methods throughout the design process in a coordinated, traceable, and informed way, promoting transparency. However, three conceptual issues emerged from this study, calling for caution in the use of off-the-shelf AD notions in a field which presents some critical differences with the product design field.

The first issue identified by this research concerns limitations to the possibility to apply zigzagging in the AEC design practice beyond the boundaries of each of the prescribed project development stages. As a matter of fact, these are highly regulated by core statutory process approval points and formally stated in contracts, meaning choices cannot be changed after these points unless external conditions allow. Nonetheless, future research could clarify if AD can play a role in responding to this challenge by facilitating the coordinated implementation of Soft-Landing principles throughout the design process. One area of interest is the use of AD to coordinate how the different briefing methods can be used to map stakeholders' needs in the zigzagging between the Customer and Functional domains as well as between the Functional, Physical and Process Domains. From an AEC design perspective, exploring this issue provides opportunities to build a sufficiently complete problem framing for staggered project development. From an AD development perspective, this opens a debate on the opportunity to have domain-specific guidance to capture a complete set of requirements and constraints (possibly considering FRs and non-FRs) to respond to the specific challenges involved in designs which cannot be prototyped.

The second issue identified by this research shows the critical points in bringing AD to the AEC industry when coordinating the application of decision support methods while zigzagging from the Functional to the Physical domains. This calls for further empirical research and practice-based investigations to verify in more detail the compatibility between axioms and each of the decision support methods used by the AEC industry. Potential starting points could be to further investigate the admissibility and complementarity of: (i) 'Deterministic choice' in detailed design stages, in relation to Axiom 1; (ii) different heuristic methods in assessing non-FRs and constraints; (iii) each of the different decision analysis methods ('Cause & effect', 'Feature evaluation' and 'Risk & uncertainties'), one by one.

The third issue, however, is the most difficult one to address. It refers to the fact that the AEC deals with a prototype of one, meaning it has very limited means, if at all, to enable full zigzagging between all domains (which hinders the assessment of user/occupant satisfaction, among other things). Although the AEC industry has attempted to put in place mechanisms to transfer this assessment to the design stages by producing more sophisticated decision-making methods, much is still needed in relation to testing and deploying these methods in practice. The methods are mainly limited to assessing occupant behavior in relation to building energy consumption and need to be expanded to account for other aspects of building usage such as, for instance occupancy satisfaction. Challenges remain in relation to how this can be done so that predictability can be increased to enable the application of Axiom 2.

In a nutshell, AD seems promising to support the coordination and integration of the different methods used by the AEC industry to achieve evidence-based designs which are able to respond to current sustainability challenges. It can be useful to coordinate the different stakeholders' needs, promote the translation of design problems into sustainable design solutions, test design alternatives and control projects. The taxonomy produced to group and organize different stakeholders' needs, design, decision-making and project control methods supports new AD applications and opens new avenues for design research as well as new topics for AD development.

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## References

[1] International Living Future and Institute, "Living Building Challege 3.1 : A visionary path to a regenerative future," *Living Futur. Inst.*, vol. 31, pp. 1–82, 2016, [Online]. Available: https://living-future.org/sites/default/files/16-0504 LBC 3_1_v03-web.pdf.

[2] RIBA, "Plan of Work 2020 Overview by Royal Institute of British Architects," *Contract Adm.*, 2020, [Online]. Available: www.ribaplanofwork.com.

[3] N. Cross and N. Roozenburg, "Modelling the Design Process in Engineering and in Architecture," *J. Eng. Des.*, vol. 3, no. 4, pp. 325–337, 1992, doi: 10.1080/09544829208914765.

[4] M. Thompson and M. B. Beck, "Coping with change: urban resilience, sustainability, adaptability and path dependence. Future of cities: working paper," Foresight, Government Office for Science, London, UK, 2015. Accessed: Jun. 11, 2021. [Online]. Available: http://www.gov.uk/government/publications/future-of-cities-coping-with-

change.
[5] N. Larsson, “The Integrated Design Process ; History and Analysis,” *Int. Initiat. a Sustain. Bult Environ.*, no. May, pp. 1–16, 2009.
[6] A. Zimmerman, “Integrated Design Process Guide.” Canada Mortgage and Housing Corporation, Ottawa, 2006, [Online]. Available: http://www.smartgrowth.org.
[7] A. E. Ikudayisi, A. P. C. Chan, A. Darko, and O. B. Adegun, “Integrated design process of green building projects: A review towards assessment metrics and conceptual framework,” *J. Build. Eng.*, vol. 50, no. February, p. 104180, 2022, doi: 10.1016/j.jobe.2022.104180.
[8] N. Roozenburg and N. Cross, “Models of the design process: Integrating Across the Disciplines,” *Des. Stud.*, vol. 12, no. 4, pp. 215–220, 1991.
[9] S. MacMillan, J. Steele, S. Austin, P. Kirby, and Robin Spence, “Development and verification of a generic framework for conceptual design,” *Des. Stud.*, vol. 22, no. 2, pp. 169–191, 2001, doi: 10.1016/S0142-694X(00)00025-9.
[10] M. Marchesi and D. T. Matt, “Application of Axiomatic Design to the Design of the Built Environment: A Literature Review,” in *Axiomatic Design in Large Systems*, Cham: Springer International Publishing, 2016, pp. 151–174.
[11] M. Marchesi, J. E. Fern, and D. T. Matt, “Axiomatic Design in Large Systems,” *Axiomat. Des. Large Syst.*, pp. 175–200, 2016, doi: 10.1007/978-3-319-32388-6.
[12] M. Marchesi, S. Kim, and D. T. Matt, “IMECE2015-50517,” pp. 1–10, 2015.
[13] C. Bleil De Souza and I. Dunichkin, “Axiomatic design in regenerative urban climate adaptation,” in *Rethinking Sustainability Towards a Regenerative Economy*, M. B. Andreucci, A. Marvuglia, M. Baltov, and P. Hansen, Eds. Springer, 2021.
[14] C. Bleil de Souza, S. Tucker, S. Deme Belafi, A. Reith, and R. Hellwig, “Occupants in building design decision-making,” in *Simulation-aided occupant-centric building design: Theory, methods, and detailed case studies.*, W. O’Brien and F. Tamasebi, Eds. Taylor & Francis, 2023.
[15] N. P. Suh, *The Principles of Design*. Oxford University Press, 1990.
[16] N. P. Suh, *Axiomatic Design: Advances and Applications*. Oxford University Press, 2001.
[17] C. A. Brown and E. Rauch, “Axiomatic Design for Creativity, Sustainability, and Industry 4.0,” *MATEC Web Conf.*, vol. 301, p. 00016, 2019, doi: 10.1051/matecconf/201930100016.
[18] D. Schon, “The Reflective Practitioner : How Professionals Think in Action,” *Ashgate Publishing Limited*, 1991. .
[19] J. C. Jones, *Design Methods: Seeds of human futures*. John Wiley & Sons, 1980.
[20] EN ISO 19650-1, “Organization and digitization of information about buildings and civil engineering works , including building information modelling ( BIM ) - Information management using building information modelling. Part 1: Concepts and principles,” pp. 1–46, 2018.
[21] G. A. Hazelrigg, *Fundamentals of Decision Making: For engineering design*. Neils Corp, 2012.
[22] H. A. Simon, *The sciences of the artificial*, 3rd Editio. Cambridge, MA: MIT Press, 1996.
[23] K. Hammond, “Judgement and decision making in dynamic tasks.,” *Inf. Decis. Technol.*,

vol. 14, pp. 3–14, 1988.

[24] A. Tversky, “Elimination by aspects: A theory of choice,” *Psychol. Rev.*, vol. 79, no. 4, pp. 281–299, 1972.

[25] S. Moghtadernejad, L. E. Chouinard, and M. S. Mirza, “Multi-criteria decision-making methods for preliminary design of sustainable facades,” *J. Build. Eng.*, vol. 19, pp. 181–190, Sep. 2018, doi: 10.1016/J.JOBE.2018.05.006.

[26] I. Loche, C. Bleil de Souza, A. B. Spaeth, and L. O. Neves, “Decision-making pathways to daylight efficiency for office buildings with balconies in the tropics,” *J. Build. Eng.*, vol. 43, no. April, p. 102596, 2021, doi: 10.1016/j.jobe.2021.102596.

[27] C. J. Hopfe and J. L. M. Hensen, “Uncertainty analysis in building performance simulation for design support,” *Energy Build.*, vol. 43, no. 10, pp. 2798–2805, 2011, doi: 10.1016/j.enbuild.2011.06.034.

[28] M. Agarwal, “Solar potential in early neighborhood design,” 2016.

[29] Building Services Research and Information Association - BSRIA, “Soft Landings Core Principles 2nd Edition,” *Constr. Res. Innov.*, 2018.

[30] N. Cass and E. Shove, “Standards? Whose standards?,” *Archit. Sci. Rev.*, vol. 61, no. 5, pp. 272–279, 2018, doi: 10.1080/00038628.2018.1502158.

[31] RIBA, “Post occupancy evaluation: An essential tool to improve the built environment,” London, UK, 2008. doi: 10.4324/9780080518251.

[32] J. S. Wong and J. Yang, “Research and application of Building Information Modelling (BIM) in the Architecture, Engineering and Construction (AEC) industry : a review and direction for future research,” in *Proceedings of the 6th International Conference on Innovation in Architecture, Engineering and Construction (AEC)*, 2010, pp. 356–365.

[33] “Brickschema,” 2022. https://brickschema.org/.

[34] C. A. Brown, “Axiomatic Design of Manufacturing Processes,” *Eight Interational Conf. Axiomat. Des. - ICAD 2014*, 2014.

[35] K. Frampton, *Studies in Tectonic Culture*. Harvard University; Graduate School of Design, 1985.

[36] A. Deplazes, *Constructing Architecture: Materials, Processes, Structures. A Handbook*, 4th ed. Birkhauser, 2018.

[37] M. K. Thompson, “Improving the requirements process in Axiomatic Design Theory,” *CIRP Ann.*, vol. 62, no. 1, pp. 115–118, Jan. 2013, doi: 10.1016/J.CIRP.2013.03.114.

[38] M. K. Thompson, “A Classification of Procedural Errors in the Definition of Functional Requirements in Axiomatic Design Theory,” *Proc. ICAD2013, Seventh Int. Conf. Axiomat. Des.*, 2013, [Online]. Available: http://www.mkthompson.net/wp-content/uploads/2013/06/ICAD2013-16-Thompson-FR-Error-Classification.pdf.

[39] S. D. Eppinger and T. R. Browning, *Design Structure Matrix Methods and Applications*. MIT Press, 2012.

[40] K. T. Ulrich, S. D. Eppinger, and M. C. Yang, *Product Design and Development*. McGraw Hill Education (India) Private Limited, 2019.

[41] N. P. Suh, “Design Systems,” *CIRP Ann.*, vol. 46, no. 1, pp. 75–80, 1997, doi: 10.1145/3380851.3416743.

[42] S. P. S. Padala, “Application of Axiomatic Design and Design Structure Matrix for Early Identification of Changes in Construction Projects,” *J. Inst. Eng. Ser. A*, vol. 103, no. 2, pp. 647–661, 2022, doi: 10.1007/s40030-021-00612-2.