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RESEARCH ARTICLE

Holistic sustainability: advancing interdisciplinary building design through tools and data in Denmark

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Abstract

Sustainable housing and buildings constitute a fundamental part of the future urban fabric. This study aims at clarifying how different actors employ parameters of sustainability in building design and what enables the holistic perspective of the interrelating social, economic and environmental parameters. Interviews with building developers and designers show that decision support tools are used late in the design process and commonly focused on single parameters of sustainability. The analysis shows how practitioners of the planning and early design phases operate at general levels of geometrical clusters and volumes but must continuously evaluate each project from the perspective of the specifications of end-users and the public, to ensure holistic sustainability. This opposing relationship between need and availability of general and specific data, however, challenges the implementation of holistic sustainability. Advancing the interdisciplinary, holistic building design requires systematic aggregation of data from executed projects of this data into applicable rules-of-thumb. In parallel, future tools for simulation and dialogue must employ a broader scope of sustainability parameters. The conceptual frameworks of data and tools presented in this study can be used as a backdrop for developing sectoral initiatives to enable holistic decisions in the early stages of sustainable building design.

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Keywords:

Holistic sustainability, building design stages, sustainability parameters, decision support tools, data and knowledge management.

Introduction

More than half of the world's population live in cities and urbanisation is expected to intensify within the next couple of decades (Seto, Parnell and Elmqvist, 2013). To avoid slum and urban sprawl, carefully planned development and densification of urban areas are matters of concern in many cities around the world. Urban regeneration projects are important to assist societal change and the transformation processes that convert the use of an urban area into another type of use, for instance brown field development of previous industrial sites and districts (European Commission, 2009).

Roberts (2000) defines urban regeneration as a comprehensive and integrated vision and action to address urban problems through lasting improvements in the conditions of an area. Preferably, these conditions span economic, physical, social and environmental aspects, and require strategic partnerships between several stakeholders to succeed (ibid.). Likewise, this focus on cross-cutting issues is a main characteristic of the current sustainability agenda, which seeks to balance holistic solutions between economic, social and environmental concerns.

Sustainable housing and buildings in general, are often regarded as key elements in urban areas of redevelopment (Zheng, Shen and Wang, 2014). The buildings as physical entities form a central part of the urban fabric. As such, individual building projects resemble, in a minor scale, the processes of larger scale urban projects. Since the building scale projects are what collectively make up the urban scale projects, the building scale projects are far more numerous. From this follows that experience embedded within the actors about sustainable building projects is more comprehensive than the experience with larger scale urban projects. Learnings from the profound body of knowledge from building projects may, then, be transferred to and used in the context of urban projects.

Several studies point to the fact that the early stages of construction design is the preferred area of intervention in order to ensure sustainably oriented projects (Häkkinen, et al., 2015; Marsh, 2016; Russell-Smith, et al.,2015). However, research also highlights how sustainability specialists are not always involved throughout the planning process which points to the holistic approach being overruled by factors e.g. economy, in the planning process (Akotia and Opoku, 2018).

In parallel with the need for holistic planning of the urban structures, industrialisation has spurred the specialisation of a range of competences with different actors of the individual projects (Antonelli, 1999). Each specialisation brings about a highly specialised knowledge of one specific area. However, this specialised knowledge is not automatically put into context with the remaining parameters that influence the design process.

In the field of construction, knowledge has traditionally been built through experience and the extended perspective of building and construction, and this aggregation of experience has correspondingly been a process spread over generations (Anumba, Egbu and Carrillo, 2005). The industrial development, with its speed of development has challenged this mode of knowledge accumulation. Most recently, the rapid development of information and communications technology has generated a constant stream of new tools and methods

(Piccarozzi, Aquilani and Gatti, 2018). Different stakeholders are organised to enable the common construction project, however this organisation is at the same time characterised by internal competition. It creates a situation that inhibits the creation of knowledge concerning how a building interacts with the environment, the surrounding city, and the people.

This seeming paradox of a demand for holistic planning at a time of highly specialised knowledge in single-parameter areas of sustainability leads to the research question of the current paper:

- How is the holistic view on sustainability in construction projects operationalised and/or constrained throughout the design process and which measures may improve the incorporation of holistic sustainability?

Background

HOLISTICALLY ADDRESSING SUSTAINABILITY

Sustainable development denotes the urgent area of focus that concerns the need to stay within the biophysical boundaries of the planet as well as providing residents and users of the built environment with sufficient levels of economic and social wellbeing (UNEP, 2012). As outlined by Rockström, et al. (2009) in the concept of planetary boundaries, specific and interlinked thresholds are in place for defined environmental areas of concern, e.g. global warming or biodiversity loss. These boundaries reflect the maximum biophysical capacity to absorb the pressure put on the global environmental system by humankind.

A linking of the biophysical boundaries to the economic and social aspects of sustainability is found in Raworth's concept of 'doughnut economy' (Raworth, 2012). This conceptual framing of sustainable development emphasises the safe, economical operating space somewhere between the environmental ceiling (i.e. the biophysical boundaries) and the social foundation (i.e. sufficient levels of food, equity, health etc.).

The classical visualisation of sustainable development is set via the 'Three Pillars of Sustainability' as shown in Figure 1. Of unknown origin, the three-pillar model emerged in the 1980's (see e.g. Brown et al., 1987) and has been widely applied. Purvis, Mao and Robinson (2019) conclude that operational frameworks based on the model face difficulties due to the lack of rigor in the theoretical underpinnings of the three-pillar paradigm. However, the figure illustrates vividly the three individual core aspects as well as the holistic integration of these. Further, the pillars express a certain depth that is of relevance when discussing specialisation within specific, measurable parameters.

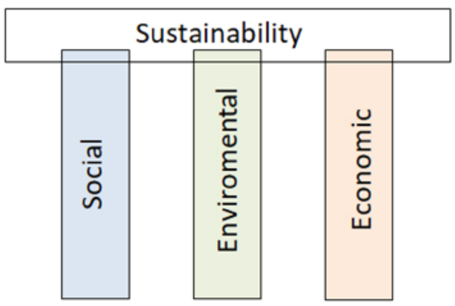

Figure 1 The conceptual three-pillar model of sustinability and its three contributing, core themes.

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SUSTAINABILITY IN THE BUILT ENVIRONMENT

Tackling the interdisciplinary nature of sustainability on a practical level in building projects is regarded as being a complex and time-consuming manoeuvre (Peace, et al., 2018; Schlanbusch, et al., 2016). Evans and Jones (2008) argue that the mere concept of using sustainability as a dialogic frame of reference, a 'shared territory', can generate creative and sustainable outcomes without reducing the process to an exercise in meeting certain benchmarks. However, to meet the targets set forth by the sustainable development goals, some level of measurable outcome is needed to document progress and safeguard the operating space within the planetary boundaries. The measurable part of sustainability is frequently integrated in the design process of individual building designs via specific tools for example environmental performance such as life cycle assessment or via more broadly oriented reporting tools such as BREEAM or DGNB. In spite of the broad scope laid out by these sustainability reporting tools, they are criticised by research for applying non-scientific benchmarks and scores (Siew, Balatbat and Carmichael, 2013), for not sufficiently addressing cultural and economic issues (Ameen, Mourshed and Li, 2015), and for addressing sustainability issues through compartmentalisation, i.e. separating the economic, environmental, and social dimensions (Lozano and Huisingh, 2011). Different types of tools in use in the construction industry are the software options for simulation or calculation. These are mainly evaluative tools and developed from a product-oriented understanding of construction, e.g. for documentation, to ensure building code compliance, or to evaluate the performance of a few alternative designs or systems (Østergård, Jensen and Maagaard, 2016). These are purposes that rarely correspond to the basic needs of the early stages of design for conceptualising and analysing.

At a regulatory level, building and planning regulations govern selected aspects that only in some cases relate to practices of sustainable buildings (Mortensen and Birgisdóttir, 2016). Recently, several countries have been preparing further regulation to deal with the environmental impacts of buildings (Lützkendorf, 2017). A broader view on sustainability is furthermore investigated in, for instance, Denmark by the preparation of a voluntary sustainability code for implementation in the building regulations (Mortensen, Kanafani and Aggerholm, 2018). The categories and parameters of sustainable building practice forming the background for this code was defined based on a survey conducted for the Danish Energy Agency in 2013 (Birgisdottir, et al., 2013) and presented in Table 1. However, despite several sustainability initiatives launched by regulatory bodies as well as certification systems, there is a lack of guidance for designers and planners on how to deal with the interdisciplinary and holistic aspects of sustainable building practice.

Table 1 The parameters of sustainability and their categories (Birgisdottir, et al. 2013).

Category	Prefix	Parameter
Environment	Environmental impact	Energy
		Materials
		Resources
	Consumption of	Energy
		Materials
		Resources

Table 1 continued

Category	Prefix	Parameter
		Chemicals
Economy	Cost	Construction
		Operation
	Quality	Rental price
		Rent
		User productivity performance
		Value stability
		Funding
Social	Indoor Climate	Thermal comfort
		Air quality
		Acoustics
		Visual comfort
	High degree of	Safety
		Access
	Good	Architecture
		Outdoor facilities
		Community
	Closeness	Means of transport

Methods and materials

FRAMEWORK FOR UNDERSTANDING HOLISM AND INTERACTIONS AT DIFFERENT LEVELS

The digital tools for handling information build on representations or data from a range of different fields of knowledge. One of the fundamental models for understanding data in the literature of information systems is the data-information-knowledge-wisdom hierarchy (DIKW) (Ackoff, 1989), as presented in Figure 2. Data are symbols that, when presented and combined in a particular way and related to a particular context, become information. The two first levels are embedded in both people and systems, whereas knowledge and wisdom are embedded in the individual and developed over time. Knowledge "[…] provides the means by which these data and information can be interpreted" (Newell, et al., 2002, p.102), and wisdom is a personal and unique process of judgement, by ethical and aesthetic values. The model has been diligently used, criticised, and refined. However, the model seems sufficiently robust, as articles, where the approach of the model is discussed, rarely succeed in establishing alternatives. For example, Frické (2009) recommends that the pyramid be abolished, but also states that "[t]his paper does not attempt to replace the pyramid with another structure" (ibid, p.132).

Jones (2019) argues that data are never objective representations, but constructions based on source, epistemology, purpose, and intended use. He distinguishes between “data in principle” and “data in practice”, and encourages a more acute awareness of the production and use of data in situated practices. The design process aiming for synthesis (a whole which is greater than the sum of its parts) resembles the levels of knowledge and wisdom in the DIKW model. Bellinger, Castro and Mills (2004) explain the transformation to a higher level (a synthesis) as supported by different modes of understandings, of relations, patterns, and principles. The DIKW model is employed in this study as an analytical framework for the use of data and tools throughout the early design stages. In the perspective of this use, the levels form a continuum (Rowley, 2007) of representation at different levels of abstraction.

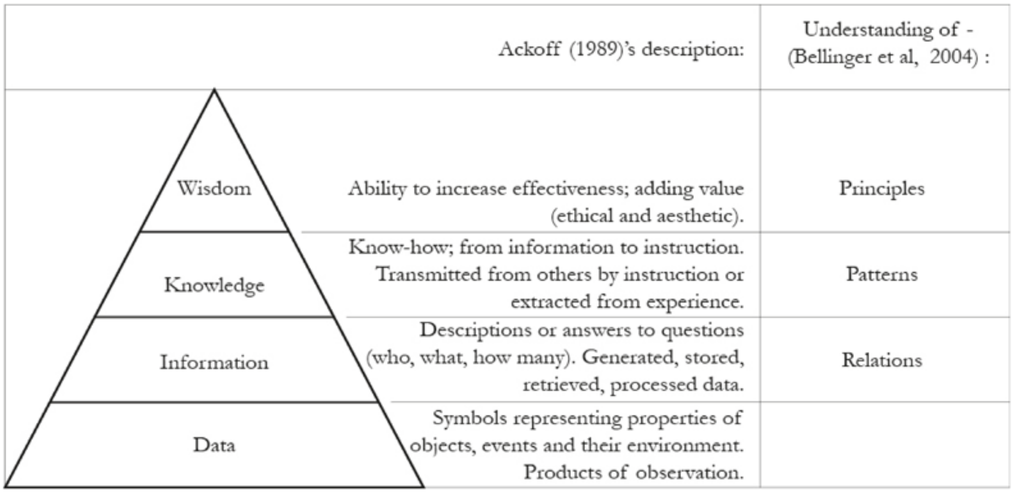

Figure 2 The data to wisdom hierarchy.

EMPIRICAL BACKGROUND

Empirical data was sourced from two separate interactions with relevant actors from the industry. First, a series of interviews was carried out, covering a total of 29 interview subjects with different roles from the first three phases of the building design process as presented in Figure 3.

Figure 3 The phases of Danish building industry (FRI & Danske Ark, 2012). The phases in this article is.

The 29 interviewees represent 24 companies, from the size of one-(wo)man businesses to companies of more than 15,000 employees. Only companies including some level of sustainability measures in their professional work were selected. The interview subjects are building industry professionals, mainly consultants and building developers/owners, representing the two most urbanised areas of Denmark, i.e. the Copenhagen and Aarhus regions. They were invited for interview via either personal contact or via social media posts by the research team.

Table 2 Details of interview subjects and their affiliation.

Subject	Professional profile	Company type	Number of employees in DK
#1	Engineer	Consulting architects	550
#2	Engineer	Consulting engineers	14000
#3	Engineer	Consulting engineers	179
#4	Engineer	Consulting architects and engineers	92
#5	Architect	Consulting architects	82
#6	Architect	Developer/ contractor	17800
#7	Architect	Consulting architects	250
#8	Architect	Consulting architects	1
#9	Architect	Consulting architects	300
#10	Architect	Consulting architects	2
#11	Architect	Consulting architects	2
#12	Architect	Consulting architects	9
#13	Architect	Consulting architects	38
#14	Architect	Consulting architects	300
#15	Architect	Consulting architects	73
#16	Architect	Consulting architects	73
#17	Chief consultant	Municipality, Property Management	90
#18	Architect	Municipality, Property Management	90
#19	Architect	University, Campus Service (project leader)	9000
#20	Team leader	University	9000
#21	Project director	Pension fund	270
#22	Engineer	Consulting engineers	800
#23	Industrial designer	Software developer	1
#24	Architect	Manufactoring company	2600
#25	Engineer	Manufactoring company	2600
#26	Engineer	University	3700
#27	Designer	Manufactoring company	600
#28	Engineer	Non-profit membership organization	11
#29	Architect	Non-profit association/ University	-

The interviewees, summed up in Table 2, represent either the defining role (e.g. the building owner/developer), the initial design role (e.g. architectural consultants), the detailed design role (e.g. engineering consultants), or the tool developers. The questions of the interviews were tailored to some degree to the specific group, addressing their specific roles in the design phases. The semi-structured interviews lasted 1-1½ hours, concerned their perception of working with sustainability parameters (i.e. the list in Table1) in the design phases and included following questions:

- Which parameters for sustainability are employed in the overall design process?
- Which tools are applied in the design process?
- At which phase are the parameters and tools applied?
- Which are the company's needs and challenges for processing sustainability?
- How is "holistic" understood and put into practice?
- Is post-occupancy data gathered? If so, is this data translated into future requirements?

The interviews were audio-recorded and transcribed. Key messages and analytical findings from the interviews were then presented for validation and/or in-depth commenting at two subsequent open workshops.

The workshops constitute the second step of the empirical data collection. The two workshops were held in the course of six months and were attended by a total of 107 people from the building industry. A range of different actors were represented at the workshops, including research and education, consultancies, municipalities, trade associations, and software developers. The participants discussed the following topics:

- Accumulation- and sharing of knowledge/experience
- Precision of data (from experience or algorithms?)
- Interaction of tools
- Usability of tools
- Sustainability and forms of tender

Minutes from the workshops were elaborated and used for further qualification of the concepts presented in this paper.

DATA ANALYSIS

The empirical material was mapped and classified within the phases of building design, as shown above in Figure 3 and in the 24 parameters of sustainability listed in Table 1.

On a meta-level, the design process is represented by the three stages of Idea, Design brief and Project design (see Figure 3). For the current analysis of parameters, the three meta-stages represent three distinct levels at which the design project takes into account specific parameters of sustainability and uses different types of tools to support the decision-making process. This three-level approach is applied in mapping the statements from the interviewees regarding their application of sustainability parameters and tool uses.

All statements referring to the parameters directly or using corresponding terms were categorised. The material was processed at three levels: 1) At the level of the individual interview in order to obtain an understanding of the specific experiences of operationalising the parameters. 2) At the level of respective groups of profession in order to explore possible divergences of the different actors involved. And finally, 3) at a general level to address the design phases as such, across the field of construction.

In order to unfold the conditions for holistic planning throughout the design stages, the data-information-knowledge-wisdom hierarchy (see Figure 2), was employed as a framework for further analyses of the empirical material.

Results

PARAMETERS IN USE AT THE DIFFERENT DESIGN STAGES

Table 3 presents the mapping of the sustainability parameters mentioned by the initiating actor, i.e. client and client's representative, in relation to the focus of the different design stages.

Table 3 Percentages denotes the frequency of specific parameters mentioned by clients and they representatives.

Idea	Design brief	Project design
75 % Cost	25 % Energy	50 % Materials
75 % Community	25 % Indoor climate	25 % Cost
25 % Visual comfort	25 % Materials	
25 % Outdoor facilities		

'Cost' was one of the two most common parameters for the initiating actors for the idea stage, though not mentioned in association with the design brief, but brought up again as part of the project design. The other three parameters stressed for the idea stage, 'community', 'visual comfort', and 'outdoor facilities', were not transferred to the following stages. 'Materials' were mentioned for the last two stages, and most frequently in the last stage of project design.

Table 4 Percentages denotes the frequency of specific parameters mentioned by architect and engineers.

Idea	Design brief	Project design
63 % Visual comfort	64 % Materials	54 % Materials
63 % Architecture	27 % Cost	18 % Cost
27 % Materials	18 % Indoor climate	18 % Indoor climate
9 % Community	9 % Energy	
9 % Cost		

Table 4 maps the sustainability parameters mentioned by the designing actor, i.e. architects and engineers, in relation to the different design stages. 'Architecture' and 'visual comfort' were the most common parameter mentioned by the architects and engineers for the idea stage, followed by 'materials', 'community', and 'cost'. 'Materials' and 'cost' were mentioned for all three stages of the design process, while 'indoor climate' was mentioned for the last two stages.

TOOLS IN USE AT DIFFERENT DESIGN STAGES

Apart from addressing the sustainability parameters in focus, the interviewees and workshop participants were asked to specify the tools that they used for decision-support in the integration of sustainability in the design process. The tools mentioned are presented in Table 5 in a schematic categorisation of types. Note that several of the stand-alone tools are interoperable with commonly used architectural design tools such as Sketch-up, Rhino or Revit. In addition to the digital tools, several consultants were employing analogue tools such as printed sheets or game boards in the early stages of building design. Some were used as tools for dialogue in discussing sustainability with the client, others as design tools in processing pro's and con's based on qualities, parameters, and building elements.

Table 5 Tools for decision-support mentioned by interviewees.

Stand-alone tools	Scripts/Plug-ins for design and/or stand-alone tools	Certification schemes	Other
IESVE	MOE holistic design	DGNB	Dialogue-tools
Velux Daylight Visualizer	Dynamo/Grasshopper/ Ladybug	LEED	Rules-of-thumb
Velux EIC Visualizer		BREEAM	Sustainability guidelines
LCAbyg		Active House	
LCCbyg		Passive House	
EnergyPlus			
BE15			
BSiM			
One-Click LCA			
LCA Profiles			

ACTOR-DEFINED GAPS IN THE INTEGRATION OF HOLISTIC SUSTAINABILITY

Across the initial interviews, a pattern of relatively identical requests and problematic issues was drawn concerning holistic sustainability. These topics were used as a point of departure and focus area in the subsequent workshops. Needs and problem areas were then further discussed in the workshop, uncovering the participating companies' perception of issues. The participants' responses were processed in group discussions and finally presented for verification in plenary.

The needs primarily concerned a desire to acquire:

- Intuitive tools that are able to generate project data for decision-support in the early phases of the design process
- A systematic accumulation of experience that can be translated into a set of easily applicable rules of thumb

The problem areas most frequently discussed were:

- The current tools for decision-support are knowledge/data-heavy
- There is a growing gap of understanding between the professional groups
- There is a lack of data collection in the field of construction

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Analysis

PARAMETERS

One of the needs outlined by actors was to be able to generate project data for decision-support in the early phases of the design process. This need relates to one of the problems mentioned, namely the problem of the industry not collecting data. A closer look at the current application and use of sustainability parameters within the design phases (see Table 3 and 4) reveals how different understandings of the single parameters are also at play in-between the different actors, which raises the question of which data is to be collected, and to satisfy whom?

'Materials' was mentioned in light of different underlying sustainability parameters, e.g. in the idea phase as an aesthetic part of the conceptual design or as an estimation of resource use. However, in the project design, materials were addressed in terms of their environmental footprint, often quantified via life cycle assessments (LCA).

Similarly, the parameter 'Cost' had different notions depending on the actor role addressing it and on the design stage in which it was employed. Thus, the initiating actor role described costs and financial budgets as defining the investment-based financial frame of the overall project. Architects and engineers addressed the financial frame as a restricting factor in manoeuvring in the design brief and project design: "The financial framework locks many of the parameters awfully early in the process" (Architect #13).

The look at 'Cost' also changed between the two groups throughout the phases. In the idea phase, it was a major focus of the client and not mentioned by the design team. In the design brief, focus was flipped as the design team conducted calculations to assure that the design-parameters applied in the idea phase complied with the financial framework; and finally 'cost' was a focus for both parts in the project design. However, one may argue that the 'cost' was implicitly embedded in the considerations about designing the geometry and net areas of the building, due to the financial framework set by the client, e.g. a set budget for a building that provides workspace for 1000 employees. Furthermore, 'cost' was, in the project design, associated with the life cycle costing (LCC) calculations that were elaborated, e.g. as part of a certification scheme for sustainable buildings.

Where the idea phase seems the most divergent across the two groups, there is more overlap in the design brief with a common focus on the parameters of energy, materials, and indoor climate. In the project design, the project was so developed that more precise calculations focusing on the materials could be implemented. Changes in materials, quantities, or types affect the cost, and both 'materials' and 'cost' were addressed by both parties. One might say that the focus and understanding of parameters converged in the project design.

Some of the parameters addressed in Table 3 and 4 were described in broader terms than the classification of categories, prefixes, and parameters in Table 1. 'Indoor climate' is a prefix for a range of sub-parameters, but was articulated as a parameter in the interviews. However, this covers a range of different aspects. Daylight, which was mentioned frequently by the architects, is covered by 'visual comfort', next to 'thermal comfort', 'air quality', and 'acoustics' – but it is unclear whether they meant all of these four parameters when referring to 'indoor climate'. 'Architecture' was a parameter mentioned by all interviewed architects. Elaborated in more detail, the interviewees saw 'Architecture' as a combination of, primarily, three aspects;

light/visual comfort, geometry, and materials. The three aspects in combination also denote the conceptual design, which presents a defining focus for the early design and the idea stage.

DIGITAL TOOLS AND WORKAROUNDS IN THE EARLY DESIGN

The majority of digital tools addressed in the interviews (see Table 5) target decision-support in the project design, i.e. simulation and calculations of the final version of the project design. Green building certification schemes as well as regulations are focused on the actual construction's performance measures and thus draw on data from the physical building structure.

While discussing the timing issue of data accumulation in one of the workshops, a suggestion was put forward on the concept of replacing data collection and simulations from each physical building project with data from statistical models. Aggregation of this statistical data was suggested to occur by artificial intelligence to support the decision-making processes. Theoretically, the model would lead to the best possible solution for a sustainable design because all interactions of all the different parameters were covered in the statistical model. However, the aggregation algorithms would need to be developed and verified from a large-scale data input from real-life, constructed buildings, which is exactly what is currently lacking. This paradox of the missing project-specific data in the early design phases thus continues to be one of the main problems for handling sustainability in the early phases of design.

Another, frequently employed, practice of relating experience from earlier projects to other projects in the early phases is 'rules of thumb'. These are simple rules, often correlating a few design parameters, e.g. the correlation of a building volume and the material consumption, or the size of a dwelling's repository (as a given percentage of the utility area) in relation to the construction costs. Rules of thumb are based on previous knowledge and experiences and condensed. However, what was voiced as a limitation is the fact that rules of thumb only correlate few parameters at the time and thus fail to address the truly holistic perspective. Furthermore, the rules of thumb are embedded within single individuals or organizations and not available for the sector as a whole.

The combination of different data (in all the tools applied) resembles information in the hierarchy of knowledge (See Figure 2), while the rules of thumb represent experience or knowledge from previous work resembling the present project. Operationalizing and contextualising the data to other data, to the specific project, to the client, to future users, and to the site of construction is all part of advancing information to the level of knowledge.

In this way, a project develops gradually from high level of abstraction to higher level of specification/concretisation. At the same time the knowledge embedded in the project changes from 'wisdom' that are embedded in the abstract decisions to empirical data in the specified solutions.

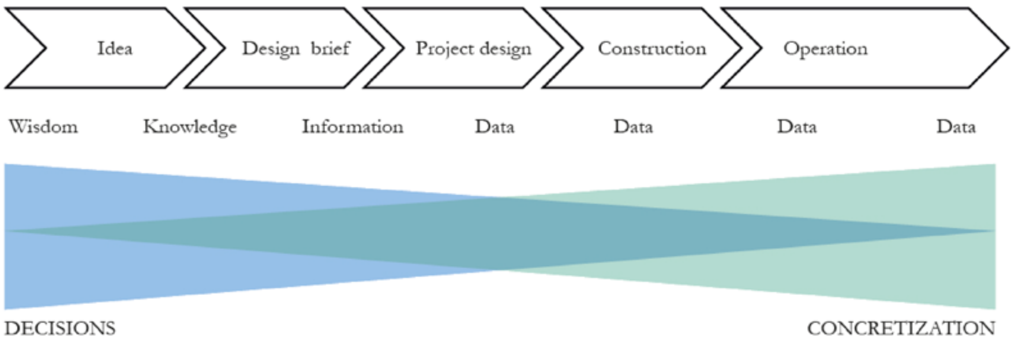

Figure 4 The relation between the types of knowledge that are applied and embedded in the design decisions.

Looking at the design process, the stated demand for rules of thumb associates with what Schön (2016) calls "reflection-in-action". The practitioner draws from a repertoire of experience and normative design domains and, in the process of understanding the problem and solution, has a transactional relation to the very situation, navigating complexity by different modes of design. Traditionally, an architect employs a range of different tools in the early design – sketches, drawings, models, to enable a reflective process to work simultaneously across scales, zooming in on the unit and out to adjust it to a broader whole. The interviews also revealed the employment of different tools through the process. For example, a given space was handled or represented by a spreadsheet, simple sketches, or in computer applications with greater complexity along the course of the design process. Different properties were assigned by different parties, depending on the competences, profession and interest. Consequently, a given parameter showed to have multiple applications throughout the design process, as demonstrated in our material by the sustainability parameters of cost, materials or indoor climate transforming throughout the phases.

LACK OF DATA ACCUMULATION AND KNOWLEDGE SHARING

One of the focal points in the workshop discussions was the lack of knowledge-sharing in the field of construction: "The industry is notoriously bad at collecting experience and sharing knowledge". This was explained by "the division of labour" between architects and engineers, and their "gap of comprehension/interpretation … which can obstruct good collaboration". The two closely related disciplines had different interpretations of a given parameter, and different understandings of how to employ it. The differences complicate the collection and/or transfer of experience and knowledge. The different approaches were perceived as: "destructive in the design process, and ultimately one party has a hold on the other" (Architect, #12). Knowledge has become a competitive factor, and not something they usually share.

In the companies that did accumulate data and experiences, accumulation was confined to limited areas of interest, whether user-experiences or installation shafts. The accumulation was unstructured and focused on productivity: "… it is limited … It belongs under 'development' which is not prioritised by the organisation/department due to time restrictions" (Engineer, #2).

Several of the interviewees stressed the value of learning from the tools and the way it qualifies their overall performance at individual, company, and industry levels: "A 'one-click' will not take us anywhere. What's to learn from it?" (Engineer, #3). Some of the software developers emphasised that the tools can be used proactively as soon as users get familiar with them, and encourage to use them iteratively: "To get the training is as important as the tools" (Engineer, #25). One of the architects considered acquiring in-house competences on energy and indoor environment as a way of supporting the interdisciplinary and holistic. One of the consultants stressed that after gaining the experience from one sustainability project, this knowledge was operationalised in later projects.

DIALOGUE TOOLS

The challenge of collaboration was addressed by some of the interviewees via specific tools for dialogue: For use in specific projects, and especially in collaborating teams, several of the interviewees described the use of analogue tools, such as game boards or guiding principles to facilitate and support the idea generation in a heterogeneous actor group or across the many parameters of sustainability. These were employed in the initial phases, often initiated by the client or the client's representative and described as an open process and a way to invite the different aspects and approaches to play. One of the interviewees addressed the public as the 'fourth client' in discussions on sustainability and the consultants' mission to be their watchdog. In this case they did not employ specific tools, but used rule of thumbs to involve the public as they are not represented in the early phases of design.

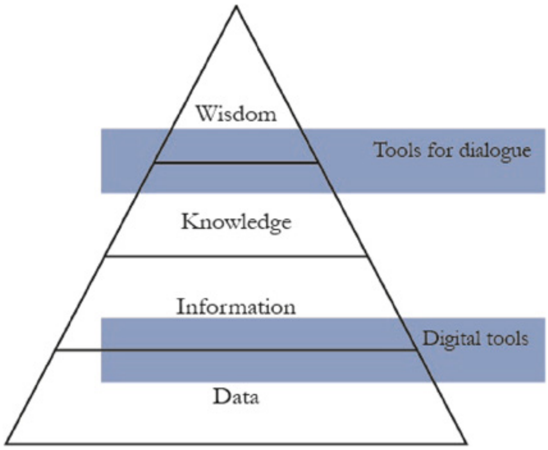

Figure 5 The digital tools and the dialogue tools placed into the knowledge hierarchy.

Figure 5 presents a mapping of the different types of the analogue and digital tools that were reported by the interviewees. Where the highly specialised and data-founded computation tools represent empirical and often quantifiable data of the current or future building (data and information level), the dialogue tools represent more abstract patterns and sometimes principles (knowledge and wisdom) from which the process of operationalising individual know-how to another specific case and context is facilitated.

Concepts for improved incorporation of holistic sustainability

TOOLS SUPPORTING HOLISTIC SUSTAINABILITY

The tools employed by designers for decision support (see Table 5) are each one operational at different phases of the design process. For instance, highly detailed calculations on thermal transmittance of the external walls require precise knowledge about the materials embedded in the wall, details that are typically known late in the design process. In this sense, the calculations of thermal transmittance of an external wall can be characterised as occurring late in the process and furthermore addressing only one single parameter associated with sustainability, in this case minimising operational energy use.

Figure 6 presents a framework for the mapping of decision-support tools based on when they are applied in the design stage and whether they span many parameters of sustainability (i.e. the beam in the pillar-beam model, Figure 1) or whether they focus on the details of single parameter performances (i.e. deep in the pillars, see Figure 1). The majority of the tools mentioned by the interviewees are 'classic' computation tools that require rather precise data input about the project at hand. The tools are thus characterised by being applied late in the design process. Further, they address mainly one parameter in detail, e.g. environmental impacts via LCA.

A few tools aim at application earlier in the design process, referred to as 'light' tools in Figure 8, these are generally characterised by containing some sort of catalogue-based simplification, e.g. pre-defined building elements and their associated life cycle CO^2-emissions. The simplification allows for application earlier in the design process. However, in terms of sustainability parameters, the scope is still narrowly defined and does not span the holistic integration of different categories.

A third category of tools refer to the 'solution space' tools that correlate selected series of sustainability parameters and allows the user to analyse and optimise the building design based on weighted performance criteria (see Østergård et al., 2016. These tools (or scripts) may operate based on input from the geometrical building models.

Rules of thumb correlate a (few) number of parameters. Due to their embedded character within individuals or within specific networks/organisation, the rules of thumb can be used from the very early stages of the building design.

Certification schemes for sustainable buildings span a large range of the parameters of sustainability. However, the documentation needed for the schemes often require input from the late phases of the design, for instance from the calculations made with the 'classic' tools. Furthermore, even though the certification scheme as a system compiles the evaluations of a large range of parameters, these parameters are not effectively correlated, rather just documented.

What seems to be missing are the tools that effectively manage to combine a large selection of correlating parameters at the early stages of the building design. As outlined through the workshop, artificial intelligence fed with big data from executed projects may be able to accommodate this need to some extent. However, numerous sustainability parameters (see Table 1) remain difficult, if not impossible, to quantify and thus cannot be represented in a model like this. This underlines the importance of generating adequate wisdom among the actors involved in the early phases of the building design. The need for transferring and aggregating data from executed projects is therefore not limited to quantifiable measurements but also heavily relies on qualitative observations and the way the quantitative and the qualitative data is processed and correlated for further use by actors.

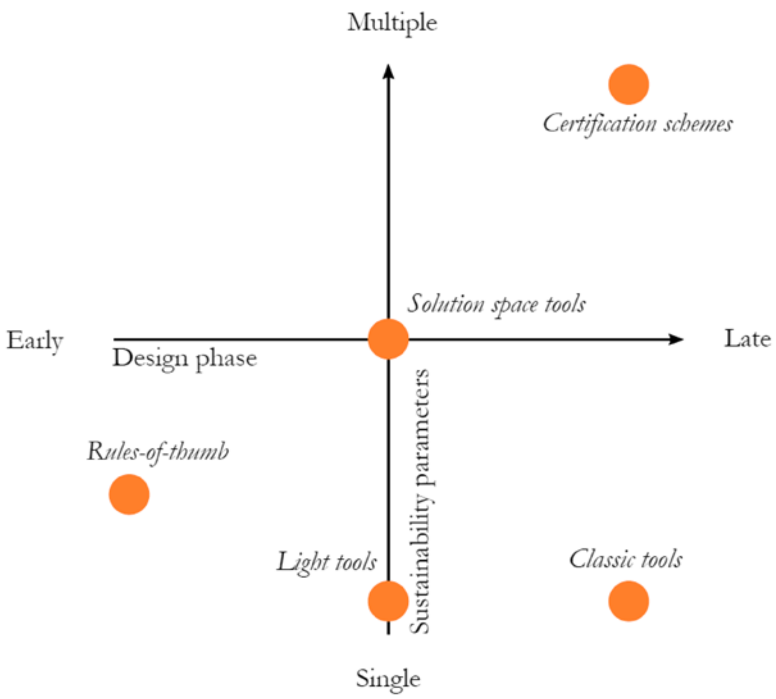

Figure 6 Tools used for decision support in sustainably oriented building projects.

DATA FLOWS AND GEOMETRY

From the outset of work on the empirical material and the subsequent analysis, the paramount importance of data aggregation and translation into knowledge and wisdom has become apparent. The considerations about sustainability throughout the design process refer to different types of virtual data, which can be categorised, as shown in Figure 7, through different geometrical levels of abstraction; cluster, volume, building part, and element.

The level of geometry and its attributes are changing throughout the project: From the early phases working on clusters and volumes, the level of abstraction decreases as the different parts and details of the project become more and more specified, to building parts and elements in the project design. As revealed in the interviews, the sustainability parameters mentioned for the initial phase included community and outdoor facilities, the urban scale, and were directed to the building scale in the succeeding phases. Furthermore, the transformation of attributes is closely related to the transformation of parameters described in the analysis. Calculation of construction costs are handled at area level in the early phases and later at the level of building parts and elements.

In this transformation process, input needs to correlate to the level of application, which means that data accumulated at component level, needs to be processed in order to be used in a more abstract and generalised level. This transformation process from the specific to the more general and abstract, resembles Bellinger, Castro and Mills (2004) different modes of understanding: from understanding relations between data, to patterns and principles. Data and information from specific and already implemented construction projects can be structured in the categories of urban fabric, building type, system supply, and component, associated to the levels of geometry, shown in Figure 7.

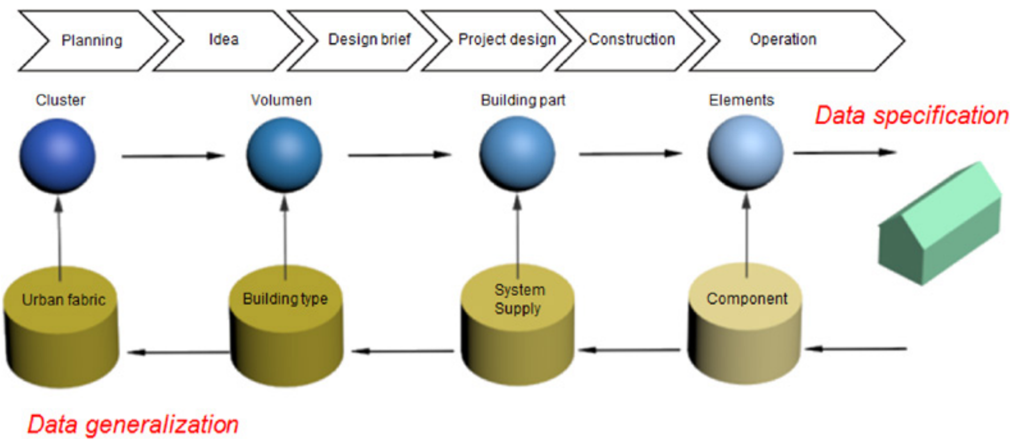

Figure 7 Framework for data specification and data flow.

The opposite data flows of the virtual data and the data from the materialised and contextualised built environment presents a primary challenge to the incorporation of a broad range of sustainability parameters in the early phases of the design. As witnessed by a range of stakeholders, the eventual collection of physical data from hand-over or in-operation context neither takes place very often nor is shared to inform actors earlier in the design process.

This in turn means that actors in the early phases of the design make design decisions unaware of the actual context in which the building will eventually operate. A systematic collection of data is needed to inform actors in the early design phases about the contextual consequences of the design decisions they make. This vast effort of data collection faces practical challenges as well as fundamental issues of responsibility for financing and processing the data.

Discussion

In the interviews, interviewees were asked about which parameters they addressed at the different phases of the initial phases of the building process on a general level. However, they were not asked whether the form of procurement plays a role for which parameters that are addressed, and the phase in which they are addressed. In reality, the form of procurement does play an important role in terms of which phase the design decisions are made. If it is a turnkey contract, the general contractor is more involved in the design brief in order to secure the buildability and reduce the costs, compared to other general contracts or individual trade contracts.

The data-information-knowledge-wisdom (DIKW) model was employed to contextualise the discussions of parameters and tools, to the field of construction and how data and information are understood and used differently by different actors and in different phases. The two groups of tools are located in each end of the DIKW model, leaving a threshold between information and knowledge that could be an important point for further tool development. Rowley (2007) address this tendency to either focus on the top or the bottom of the model, and further challenge the model by seeing it as a "continuum with different levels of meaning, structure and actionability occurring at different levels".

Digital data and information are related in the system and control-related structures (Frické, 2009) of digital tools, and form a considerable base for decision-making in both the construction industry and the digital industry, e.g. through simulations. Hence, data should be aggregated in a model that refers to the DIKW understanding, and thus be included in the chain of future decisions.

The empirical data of the current study focuses primarily on the tools and parameters. Consequently, to obtain a deeper understanding of the interpretations and the judgements at play in the levels of knowledge and wisdom, other types of research methods would be needed, e.g. observations or case studies focusing on the tacit knowledge at play in these processes.

Future research could furthermore employ other theoretical frameworks, such as the technological frames (Orlikowski and Gash, 1994), in order to gain a deeper understanding of the different rationales, incentives and barriers of the different groups.

Conclusion

Sustainable housing and buildings in general constitute a fundamental part of the future urban fabric. Urban regeneration projects aspiring for sustainable profiles can find inspiration from the more numerous building scale projects applying sustainability parameters in practice. This study contributes to the considerations of sustainable urban regeneration projects by uncovering how different actors employ parameters of sustainability in the design process and what challenges the holistic perspective of the interrelating social, economic and environmental parameters. Through a series of interviews, this study finds that actors of the initiating and the developed building design process favour different parameters of the holistic sustainability. Further, the study finds that decision support tools in use for sustainable building design are used late in the design process and commonly focused on single parameters, therefore failing the holistic perspective. Most actors rely heavily on rules-of-thumb and acquired experience for integrating sustainability in the design process. However, shared knowledge about the interaction of sustainability parameters is needed at all levels of the planning and design process. Accumulated data from executed projects may form part of this knowledge needed for future, urban projects. Still, it is not possible to quantify all the parameters of sustainability for integration in calculation tools.

The study finds that practitioners of the planning and early design phases operate at general levels of geometrical clusters and volumes, but must continuously evaluate each project in perspective of the specifications at end-users and the public to ensure holistic sustainability. This opposing relationship between need and availability of general and specific data challenges the implementation of holistic sustainability. Aggregated data is essential for the early design stages, as data must support a process where the components of the decision are only vaguely known. Hence, systematic and accessible rules-of-thumb as well as tools for dialogue may constitute a way forward in which the span and correlation of sustainability parameters becomes a fundamental part of the knowledge needed in the planning and design process.

Advancing the interdisciplinary, holistic building design requires systematic aggregation of data from executed projects and conversion of this data into applicable rules-of-thumb. In parallel, future tools for simulation as well as for dialogue must employ a broader scope of sustainability parameters. Further research is needed on how to merge different sets of data types on a practical level.

The current study contributes to future work on sustainable urban design by providing a conceptual coupling of the DIKW framework with the design stages and the data aggregation levels that are in play when gradually specifying a construction project. The conceptual frameworks of data and tools presented in this study can be used as a backdrop for developing sectoral initiatives to enable holistic decisions in the early stages of the sustainable building design.

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