Proceedings of the Design Society, Volume 6: DESIGN 2026
https://doi.org/10.1017/pds.2026.10414

Set-based design approach for renewable energy integration in social housing: design space mapping with a morphological chart

Saioa Gartzia[1,2,✉], Audrey Abi Akle[1], Michael Hamwi[1] and Iban Lizarralde[1]

[1] *Université de Bordeaux, ESTIA-Institute of Technology, EstiaR, France,*
[2] *Comité Ouvrier du Logement (COL), France*

✉ s.gartziaagirre@net.estia.fr

ABSTRACT: The EU 2050 carbon neutrality target drives growing interest in renewable energy (RE) integration in building design, yet social housing organizations face difficulties integrating them early in design due to complexity and high upfront costs. This paper presents a three-step method based on the Set Based Design approach to define the design space using a morphological chart. This offers a robust and adaptable framework to formalize and structure domain-specific knowledge, clarifies design options, and supports informed decision-making for RE integration in social housing design.

KEYWORDS: decision-making, design methodology, design tools, knowledge representation, design space exploration

1. Introduction

The building sector is currently undergoing a profound transformation in response to the European Union's objective of achieving carbon neutrality by 2050. Within this framework, decentralized renewable energy (RE) systems are gaining increasing attention as a means to reduce dependency on centralized grids and lower carbon emissions (Karunathilake et al., 2019). For social housing organizations, this transition represents both an opportunity and a challenge. In this context, social housing organizations are rethinking their role as both developers and owners. They are uniquely positioned to implement RE solutions that can contribute to environmental targets while also addressing issues of affordability and energy poverty. However, integrating these technologies into social housing projects is far from straightforward. Decision-makers in such projects often encounter difficulties in the earliest stages of the design process, when choices are most consequential. High upfront investment costs further complicate the feasibility of such initiatives. As a result, many promising solutions remain underutilized or are introduced too late in the process, leaving limited room for adjustments once the project is defined. Research has shown that the integration of RE in social housing is hindered by a complex interplay of (i) technical, (ii) organizational, and (iii) economic barriers (De Luca et al., 2020; McCabe et al., 2018; Muyingo, 2015). From a technical perspective (i), most contributions emphasize optimization methods based on algorithms and simulations. These methods are intended to support decision-making by combining variables such as climatic conditions, energy demand, and technology performance (Aruta et al., 2023; De Luca et al., 2020; Seabra et al., 2021). Yet, the majority of these studies are case-specific, tailored to a given project or geographical context (Aruta et al., 2023). Because each building is essentially a unique prototype – with its own climate, predicted energy production, and pricing policies – the methods and results developed for one case cannot easily be generalized to other projects (Dabush et al., 2023; Vallati et al., 2023). Moreover, much of this literature privileges technocratic approaches that isolate technical performance, overlooking the sociotechnical dimension of social housing projects (Moore et al., 2015; Muyingo, 2015; Vallati et al., 2023). Ownership structures,

https://doi.org/10.1017/pds.2026.10414 Published online by Cambridge University Press

governance arrangements, and management practices – factors that fundamentally shape the feasibility of RE integration – are often insufficiently addressed (McCabe et al., 2018). As a result, decision-makers remain confronted with fragmented knowledge and tools that fail to capture the full scope of RE integration challenges specific to social housing. Organizational barriers (ii) also arise from the novelty of RE integration. McCabe et al. (2018) identify issues including inappropriate management protocols, ineffective installations, poorly defined staffing roles, and limited inter-organizational cooperation. Muyingo (2015) adds that decision-making during building design is affected by insufficient technical knowledge, negative past experiences with emerging technologies, and complex administrative procedures. At the same time, integrating RE technologies transforms social housing organizations and residents into active participants in the energy value chain, moving them from passive consumers to producers or suppliers (Aparicio-Ruiz et al., 2019). Yet energy-related activities are not the core mission of these organizations, and guidance for informed decision-making is limited. Economic barriers (iii) further constrain RE adoption. High initial investment costs remain a major obstacle for social housing (De Luca et al., 2020; Moore et al., 2015), which often relies on subsidies or third-party investments. Literature has proposed various financing mechanisms and energy business models, such as government subsidies, roof leasing, energy communities, and performance contracts. Yet their viability depends on context-specific factors such as location, national policy, project parameters, investment models, and consumer profiles (Dabush et al., 2023; McCabe et al., 2018; Moore et al., 2015). In France, the multiplicity of ownership models within a single social housing program adds complexity, further increasing the range of possible configurations.

Taken together, these insights reveal that supporting decision-making for RE integration in social housing building project requires approaches that simultaneously consider technical, organizational, and economic dimensions. Decision-makers face a lack of knowledge regarding available solutions, and decisions are often made too late in the design process, limiting adjustment possibilities. Therefore, it is crucial to clearly define the design space early, to anticipate barriers and prevent potentially valuable options from being excluded. This design space must encompass three dimensions: emerging technology characteristics, social housing-specific building parameters, and emerging energy business model options. Yet, literature don't describe systematic methods to structure this domain-specific knowledge, the design space.

To address this challenge, this study is positioned within the Set-Based Design (SBD) approach, which emphasizes exploring a boarder set of alternatives before gradually narrowing down options. Here we focus specifically on early-phase design space exploration, which has the potential to formalize and structure domain-specific knowledge while supporting informed decision-making (Abi Akle et al., 2019). Building on this perspective, the paper presents a three-step methodology to map the design space of a social housing project integrating renewable energy (RE) solutions, developed with domain experts. The aim is to formalize and structure domain-specific in the early-stages of the SBD approach through a morphological chart, enabling informed decision-making in early phases of the building design process. It unfolds three main phases: (1) conducting individual interviews to identify key variables and modalities influencing the design problem; (2) applying a card-sorting technique to organize and group variables and their modalities, thereby clarifying the structure of the design space; and (3) performing a consensus analysis that highlights both agreements and disagreements among experts. The consensus analysis is crucial for detecting variables that may carry multiple or ambiguous meanings, which could otherwise lead to misinterpretation and confusion in later stages of the design process. The outcomes of these phases are synthesized into a morphological chart, which provides a structured representation of the identified variables and their possible modalities. The remainder of the paper is structured as follows: Section 2 presents the SBD approach, Section 3 details the proposed methodology for developing the morphological chart, and Section 4 presents the results obtained from applying this methodology to the RE integration in social housing, using a French social housing organization as a case study.

2. Set based design

New opportunities for RE integration require considering the combination of RE production systems, energy business models and social housing programs. Since each building project represents a unique prototype, decision makers must explore alternative solutions specific to each project during the early design stages, while also gaining knowledge to better understand and address the design problem. Moreover, the earliest decisions in the design process have the largest impact on quality and cost of the project (Toche et al., 2020). Faced with this multidimensional complexity, decision-makers often

https://doi.org/10.1017/pds.2026.10414 Published online by Cambridge University Press

overlook viable alternatives due to their limited knowledge of existing options. In this context, the SBD offers a structured approach to define and explore the design space. In fact, SBD is an approach that presents a valuable alternative to the conventional point-based design approach (Castañeda et al., 2023; Hannapel & Vlahopoulos, 2014), that prematurely selects single design solution and refine it until all stakeholders are satisfied (Castañeda et al., 2023; Toche et al., 2020). Conversely, SBD encourages the exploration of a boarder set of alternatives before gradually narrowing down options. This approach encourages collaboration by sharing and identifying areas of overlap among feasible options, enabling transparent decision-making (Castañeda et al., 2023). Since the building design process requires collaboration among professionals from different fields to define project characteristics (Castañeda et al., 2023), it appears to be a promising approach to address these challenges. Indeed, these projects are often unique and multidisciplinary, involving significant complexity, uncertainty, and high financial investment, making it crucial to explore multiple design alternatives during early stages of the project. In both academic and industrial context, three core principles SBD are outlined (Toche et al., 2020): mapping the design space, integrating though intersection and establishing feasibility. First, to map the design space, stakeholders from different disciplines start by defining feasible region for the design variables. Then, the second step focuses on integrating through intersection by identifying areas of possible overlap focusing on the feasible region (Hannapel & Vlahopoulos, 2014; Toche et al., 2020) to minimize constraints and ensure conceptual robustness. Finally in the third step, feasibility of solutions is studied before making commitments by progressively narrowing options. Toche et al. (2020) provides a literature review of SBD to identify and analyse the key factors involved in developing a methodology to transition toward SBD. Their finding reveals that, while theoretical development in the field remains limited, there is a growing interest in the diversity of contributions. Still, even if there is a growing interest, there is a lack of methods that help to clearly define the design space. Several methods that share similarities with SBD, use exploration of multiple alternatives to converge within the design space (Toche et al., 2020) : the morphological chart, the method of controlled convergence (Pugh, 1991) or the Design-Build-Test cycle (Wheelwright & Clark, 1992). Thus, this research focus on the morphological chart, as it is well-established tool that can be integrated and adapted to support the implementation of the first principle of SBD (Raudberget, 2011) : to map the design space (Zeiler, 2018).

2.1. Morphological chart

The morphological chart proves to be an effective tool for mapping the design space and formalizing knowledge across different fields. Originally developed by Zwicky (1967), the morphological chart maps the design space rather than directly solving problems and supports the exploration of alternative solutions (Hülagü, 2024; Zeiler, 2018). It enables systematic exploration of possible solutions of a design problem, by examining all combinations resulting from the systems decomposition. It also helps to discover hidden relationships and configurations that might be otherwise overlooked (Zwicky, 1967). As shown by Zeiler, (2018), this tools facilitates collaboration within multidisciplinary teams during the early conceptual design phase by enabling each discipline to contribute its perspective while organizing the available knowledge clearly. It particularly helps architects and engineers with their new role, through the effective structuration of available domain knowledge (Zeiler, 2018) and the visualization of the design space (Hülagü, 2024). In contrast to mathematical methods or simulations, the morphological chart helps in addressing complex, poorly defined problems that require qualitative exploration (Ritchey, 2014). Moreover, even non-experienced professionals can create morphological chart (Hülagü, 2024), making the tool accessible and practical for a wide range of users. This structured approach makes it particularly interesting to the integrated, multidisciplinary and complex nature of RE integration in social housing design. It provides an overview of the decomposition of a design problem's functions and the possible means (solutions) to perform each function (Smith et al., 2012). All functions must be clearly defined, with alternative solutions specified, thereby framing the design space (Zeiler, 2018). In this research, since the morphological chart is applied to a project rather than a product, functions are replaced by project variables that influence RE integration in the context of social housing, while the possible implementation options of these variables are referred as modalities. The morphological chart is represented as a matrix with columns and rows (Zeiler, 2018) (see an example in Figure 1). All variables are listed in a column and the modalities are listed in rows to the side Smith et al., 2012). The compilation of the list of desired variables and modalities needs a decomposition process (Smith et al., 2012).

https://doi.org/10.1017/pds.2026.10414 Published online by Cambridge University Press

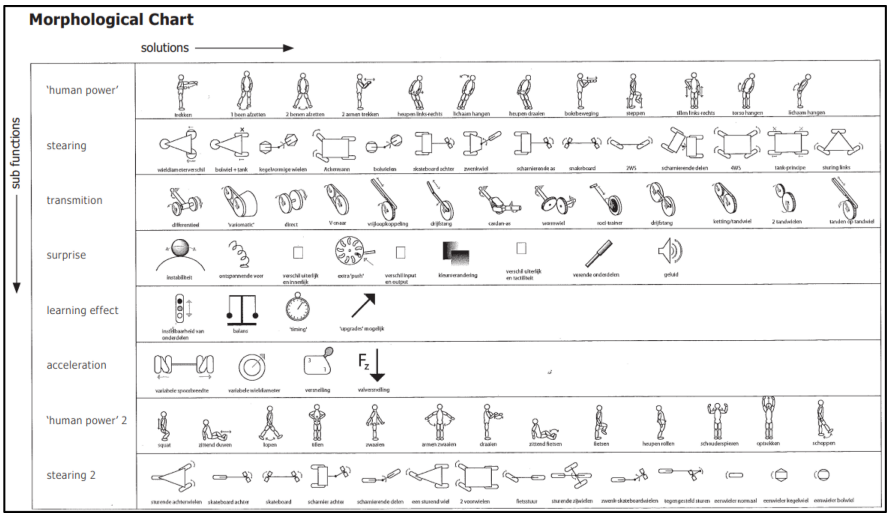


Figure 1. An example for a morphological chart from Delft Design Guide (2013)

Thus, Hülagü (2024) proposes 3 steps to create and use the morphological chart for these purposes:
1. Decomposition: Deconstruction of the system into sub-systems (Boeijen et al., 2013) to then define the list of design functions. This decomposition allows for the definition of the vertical axis of the morphological chart. Careful consideration is required when selecting these sub-systems, as they form the structural basis of the analysis.
2. Generation: Identification of possible options for each previously defined function.
3. Combination: Once the chart created, systematically explore different combinations of options across the design space to identify potential configurations. Therefore, the initial design space must be reduced, eliminating combinations that are technically, economically or contextually unrealistic.
The state of art shows that exploring a broader set of alternatives before gradually narrowing options, as in the SBD approach, provides a valuable conceptual framework for RE integration in social housing as it supports structured exploration, early-phase decision-making, and cross-disciplinary collaboration. However, it is important to clarify that although based on the principles of the SBD, this research focuses on early-stage design space mapping and exploration rather than convergence to a feasible set. Indeed, even if SBD traditionally addresses concurrent engineering context with progressive narrowing of solution sets, our work emphasizes knowledge discovery and problem understanding through structured exploration of alternative concepts prior to narrowing. In this context, methods to systematically map the design space and support early-stage exploration are limited. Morphological chart appear to offer promising solution, providing a visual and systematic approach to decompose complex problems and qualitatively explore alternative solutions (Zeiler, 2018; Zwicky, 1967). Thus this paper proposes a three-step methodology based on morphological chart creation (Hülagü, 2024), focusing on decomposition and generation phases, to map the design space. The goal is to formalize and structure domain-specific knowledge in the early-stages of the SBD approach through a morphological chart, enabling informed decision-making during early phases of the building design process, which can later guide narrowing of design solutions.

3. Methodology proposition

Mapping the design space to ensure the integrated design of social housing and RE systems is essential for formalizing relevant knowledge that supports informed decision-making. This paper proposes a step-by-step method within SBD paradigm, to map the design space for RE integration in social housing, using morphological chart. This is intended to assist social housing decision-makers in exploring solutions for their building design projects. Based on the first two stages for morphological chart creation described in Section 2.1 (decomposition and generation) (Hülagü, 2024), a three step method is proposed to decompose the design problem and generate the morphological chart (see representation in Figure 2).

https://doi.org/10.1017/pds.2026.10414 Published online by Cambridge University Press

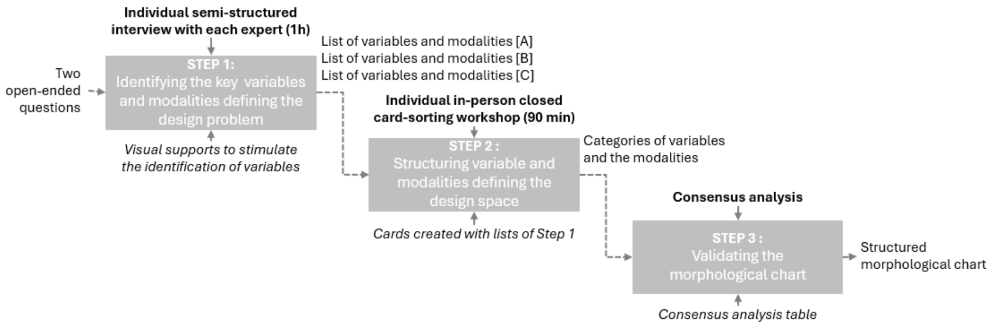


Figure 2. Proposed methodology for morphological chart co-cocreation

In the first step (1) researcher decomposes the design problem into sub-systems and identifies key variables and modalities through individual expert interviews from each sub-system, supported by visual materials (Yin, 2014). In the Step 2 (2), the researcher uses this list of variables and modalities to create cards for a closed individual in-person card-sorting workshop. Here experts are asked to assign modalities to variables according to their mental models (Conrad & Tucker, 2018). This refines the initial conceptual categories, structuring the design space free from group influence (Zimmermann, 2016), minimizing social biases (e.g. conformity, dominance behaviours), and ensuring that the collected data are both comparable and authentic. After collecting data from each workshop, the researcher codes the variables and modalities in an Excel file according to expert-proposed categories, with qualitative comments included to support later analysis of disagreement. As experts may provide different categorizations, the researcher conducts a consensus analysis in Step 3 (3) to consolidate a shared set of variables and modalities across all sub-systems, resulting in an initial design space formalized in a morphological chart. In the initial analysis the researcher first identifies areas of consensus and then the nature of disagreement for those where there is not consensus (semantic ambiguities, the multi-thematic character of certain variable, or default classifications). Depending on the type of disagreement; the researcher applies predefined analytical rules (e.g. retaining majority classification, prioritizing domain-expert justification) detailed in Section 4.2. Some cases cannot be systematically analysed, as the underlying disagreements are difficult to interpret from a qualitative point of view. To address these unsolved cases, a workshop bringing all together experts is conducted to reach a collective consensus. Detailed methodological framework of each step is detailed in Table 1.

Table 1. Methodological framework

Step	Methodological Framework	Material
1	1. Decomposition of the design problem into specific domains. 2. Selection of domain experts with at least 10 years of experience. 3. Individual semi-structured interviews with open-ended question to identify variables influencing the project within each expert's domain, supported by visual materials. 4. Identification of modalities for each identified variable.	Simulation visual supports for variable identification - Example of partially completed chart. - Domain specific documents (e.g. flyers and technical diagrams).
2	1. Creation of variable and modality cards with data from Step 1. 2. Distribution of all variable cards to ensure that the experts understand all of them. 3. Distribution of all shuffled modality cards. 4. Request experts to assign each modality to a variable they consider most appropriate. They can also create or delete modalities.	- Set of cards: variables and modalities in different formats to prevent confusion. - Blank cards for new propositions. - Erasable markers to create or modify cards.
3	1. Validation of the variable-modality assignments that have reached consensus. 2. For assignments where consensus is not reached, measurement of the level of disagreement for each pair. 3. Identification of the nature of disagreement from expert qualitative comments (e.g. "Typology is misleading; use "type" instead"). 4. Application of the strategy concerned for each disagreement reason. 5. For disagreements that cannot be classified under previous steps, a collective validation workshop with all experts.	- Excel spreadsheet to code the variable-modality assignments and the nature of disagreement.

https://doi.org/10.1017/pds.2026.10414 Published online by Cambridge University Press

All steps have been supervised by the researcher, noting qualitative insights and potential interrelations between variables. The morphological chart is then constructed using validated final set variables and modalities, with the variables displayed along vertical axis and their corresponding modalities arranged along horizontal axis.

4. Application and results

4.1. Case study description

In this research, the main objective is to formalize and structure domain-specific knowledge (initial design space) and support informed decision-making for the RE integration within social housing design. Therefore, the implementation of the proposed methodology is illustrated through its application within a French social housing organization Le Comité Ouvrier du Logement. Established in the early 1950s, this organization is a long-standing actor in the field operating both as a social housing builder and as property manager. Thus, this organization was chosen as a case study because of its extensive experience and active role in the social housing sector. Producing between 300 and 500 units per year and managing a housing stock of over 2,000 units, it is now facing new challenges. With an increasing production demand under stricter environmental regulations, the organization has begun to integrate RE solutions into its projects, although largely depending on available subsidies. Moreover, ensuring this integration requires decision-makers to navigate a broad range of RE technologies such as photovoltaic, solar thermal or biomass while aligning their choices with the specific demand-side requirements of each building program (e.g. space heating, lighting, water heating) (Aparicio-Ruiz et al., 2019; Karunathilake et al., 2019). This process also requires consideration of appropriate energy business models (Parreño-Rodriguez et al., 2023) as well as the ownership or governance structures specific to social housing. However, given the growing need to integrate RE and the relative novelty of this process, decision-makers often lack sufficient knowledge of the available solutions, which limits their ability to make fully informed decisions. Hence the importance of first clearly defining the design space to be explored during the early stages of the design process to anticipate potential barriers and ensure that valuable options are not prematurely excluded. Given the organisation's interest, expertise in the field and need to integrate RE, its participation in the development of the morphological chart offered an opportunity to collaborate with experts involved in social housing projects and to work with a committed and engaged organization.

4.2. Methodology implementation in social housing building organization

As this study focuses on integrating RE into social housing building design, the design problem was decomposed into three sub-systems: social housing programs, RE production technologies, and energy business models. Experts were identified for each sub-system based on their relevant experience: a building project coordinator from the organisation responsible for the social housing design decision-making, an entrepreneur in the RE sector with expertise in energy systems that collaborate with the organisation to support RE projects, and a member of a community-based RE production company with over 2,000 consumers experimenting with emerging business models.

Once experts were identified, individual semi-structured interviews were conducted with each of them to produce a synthetized list of variables and modalities for each sub-system. This process enabled the identification of those most relevant to the design space based on the experts' perspectives, constrains, levers and priorities. Each interview followed three stages: first, experts identified the variables influencing the integration, supported by two open-ended questions and visual materials designed to stimulate discussion; second, they reflected on the possible modalities associated with each variable; finally, the information gathered was summarized and validated with each participant to ensure accuracy and completeness. Thus, the initial list produced in Step 1 comprises 14 variables and 48 modalities for the social housing program sub-system, 6 variables and 29 modalities for the RE production technologies sub-system, and 8 variables and 28 modalities for the energy business model sub-system, a total of 28 variables and 105 modalities. All these variables and modalities were then used to create the cards for the closed individual in-person card sorting workshop (see Figure 3). The cards were designed to remain neutral and non-suggestive to minimize cognitive bias. The aim of the card-sorting technique was to organize and group variables and their modalities, thereby clarifying the structure of the design space. The variable cards were first

https://doi.org/10.1017/pds.2026.10414 Published online by Cambridge University Press

distributed to the experts for review and discussion to ensure full understanding. The shuffled modalities cards were then distributed, and experts were asked to create variable-modality groupings reflecting their individual mental models within their respective domain of expertise.



Figure 3. Phase II of morphological chart co-creation process

During the card-sorting workshop, experts considered some card irrelevant or redundant and recommended their removal. Other cards were refined to improve shared understanding among decision-makers using the chart. Regarding modalities, the analysis revealed that experts, depending on the domain of expertise, interpreted and categorised them differently. The workshop ultimately resulted in 25 variables and 119 modalities. Consequently, it was necessary to conduct a consensus analysis (step 3 of our methodology). Once the data collected, it was observed that experts reached 41,18% consensus (i.e. 49 sets), which meant that each categorization had to be examined individually. For the consensus analysis, the first step consisted of measuring the level of disagreement for each variable-modality assignment. The level of disagreement was assessed as follows:

- Complete disagreement (100%): when none of the experts proposed the same categorisation, entirely new variables or modalities were suggested, or elimination was proposed, the disagreement analysis was deferred to the final validation workshop involving all experts.
- Partial disagreement (more than 25%): The process began by identifying the source of each disagreement, drawing on the qualitative notes taken by the researcher during the card-sorting workshop. Disagreement could be attributed to:
  - Default classification: when experts placed a card by elimination strategy or necessity, without clear reasoning (e.g. “I put it here because I didn’t know where else to place it”). Here, if the disagreement did not come from the domain expert for that variable, the majority classification was retained. However, if it originated from the domain expert, the consensus analysis was done during the final group validation workshop.
  - Semantic ambiguity: when experts interpreted a concept differently depending on their area of expertise and if the disagreement came from the domain expert and could be justified with references from the scientific literature, the categorization proposed by that expert was validated. This work revealed a major challenge related to the complexity of the terminology used by different experts.
  - Multi-thematic modality: when a modality could reasonably correspond to more than one variable. In such cases, the possibility of duplicating the card was examined to determine whether this categorization would better capture the multiple thematic associations.

When disagreements could not be classified under any of these categories, a dedicated group validation workshop was organised with all experts to collectively resolve remaining cases. The proposed method enabled the resolution of 32,14% (18 sets) of the disagreement cases (56 sets in total), while the remaining variable-modality assessments (53 sets) required validation during this workshop. During the final workshop, each variable-modality assignment was reviewed one by one with all experts together. The experts first examined the nature of the disagreement and then reached a shared consensus through group discussion. The results of this research present a first version of the morphological chart, providing a clear mapping of the initial design space for RE integration in social housing (see Figure 4).

https://doi.org/10.1017/pds.2026.10414 Published online by Cambridge University Press

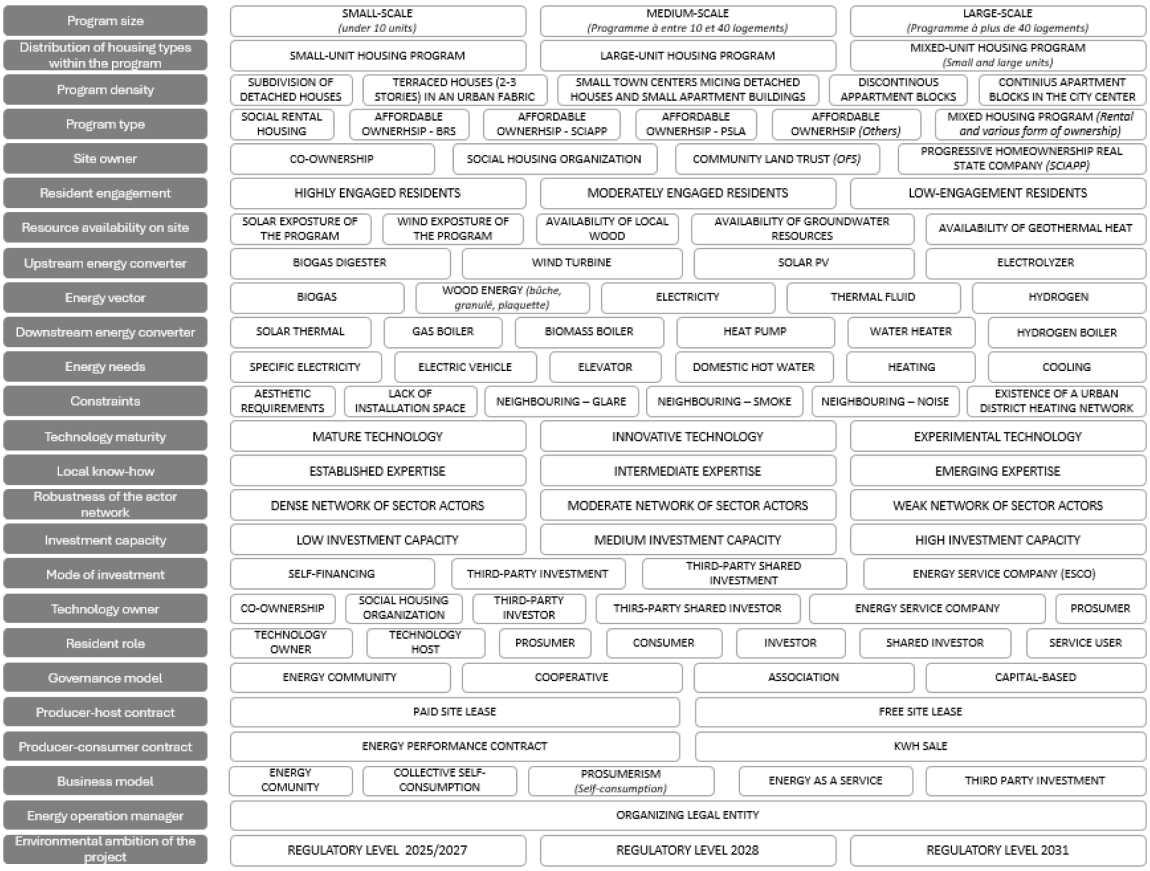


Figure 4. Consolidated version of the morphological chart

This framing serves as the foundation for defining the design space and identifying feasible regions within this context. The outcome of this methodology, the morphological chart, is presented in Figure 4, linking the identified variables and their corresponding modalities as defined through expert input. This design space mapping provides a structured understanding of the system, which is often not explicitly defined in a systematic way (Toche et al., 2020). The chosen case study offers a relevant setting to test this methodology, as it involves complex interactions between technical, social and environmental dimensions. The insights gained from the participating experts highlight the potential of the morphological chart to support informed decision-making and guide the integration of RE in social housing through a clearer understanding of the feasible design regions.

5. Discussion & conclusion

This research proposes a methodology to map the design space for RE integration in social housing, combining SBD perspective with a morphological chart as an early-stage structuring and exploratory tool. Starting with the individual identification of key variables and modalities within each domain, followed by independent expert card-sorting workshop to refine the initial conceptual categories, the process concludes by a consensus analysis of these categorizations. All these variables and modalities are formalized in a morphological chart providing structured representation of the design space for RE integration in social housing and enabling set-based design space awareness (Toche et al., 2020). This will then serve as a collaborative early-stage exploratory tool for systematically exploring and combining subsystem solutions by clarifying the sets of feasible alternatives. The morphological chart developed through this methodology enables decision-makers to visualize the breadth of the design space and consider different configurations supporting informed decision-making. It emphasizes on structuring domain-specific knowledge and progressively building shared understanding. By providing a comprehensive overview of the overall design space, this approach addresses challenges in a field often characterized by fragmented knowledge and encourages the exploration of alternative solutions that might not otherwise have been conceived by designers. In this way, it aligns with SBD principles, which has been explored from diverse perspectives in literature, including knowledge domain

https://doi.org/10.1017/pds.2026.10414 Published online by Cambridge University Press

(Toche et al., 2020). Although our research draws on the SBD principles, which encourages the exploration of a boarder set of alternatives before gradually narrowing down options, this study focuses specifically on early-stage design space mapping using the morphological chart. The aim is to support design space exploration, rather than the full implementation of SBD principles with later stages of convergence. Emphasis is placed on knowledge discovery and problem understanding through structured exploration of alternative concepts prior to narrowing. Literature shows that SBD is often combined with complementary design methods to support concept generation, exploration and selection (Castañeda et al., 2023; Toche et al., 2020). In this context, the morphological chart creation methodology complements SBD by providing a systematic way to represent the design space and solution sets, facilitating explicit design space mapping. In doing so, our work also aligns with the Design by Shopping (DBS) paradigm (Balling, 1999), which emphasizes exploration of multiple alternatives and knowledge discovery prior to convergence on specific set of feasible solutions. According to Balling (1999), the traditional optimisation-based design process which involved problem formulation, model development and algorithm execution, frequently leaves designer unsatisfied. This approach facilitates structured evaluation enabling designers to explore the design space, and then to optimise and choose a best solution from a set of possible designs, before finally developing realistic expectations with regard to what is possible (Abi Akle et al., 2019). Considering a board set of design alternatives, decision-makers learn about feasibility and relationships, to then make their choice. Moreover, Castañeda et al. (2023) already identified this approach as a complementary approach of SBD adoption in the construction industry. Therefore, it represents a promising direction for future exploration phase definition, supporting knowledge discovery and problem understanding for decision-makers, rather than relying on optimization-based design process.

Nevertheless, from a methodological perspective, this study represents limitations related to the researcher's active role in facilitating workshops and conducting the consensus analysis. Reflexive measures were implemented to mitigate potential bias, including neutral card design, individual workshops prior to group discussion, validation of syntheses with experts, explicit rules for resolving disagreements, and a final collective workshop. Nevertheless, the absence of independent coding is recognized as a limitation, and future work will include review by an uninvolved researcher. Although the proposed methodology to create the morphological chart provides a comprehensive visualization of the designs space, it does not consider the interdependencies between variables and modalities, which may generate unrealistic combinations. Future work will focus on the integration of constraints to reduce infeasible regions and filter technically, economically or contextually unrealistic options. It is also essential to establish clear operational protocols that define how decision-makers navigate the tool to enhance its usability in real design contexts. However, maintaining multiple alternatives over development phases may lead to increased costs that could limit practical applicability (Toche et al., 2020). This research also highlights gaps in current knowledge, particularly regarding emerging energy business models, emphasizing the need for accessible, structured information to support informed decision-making. In fact, even experts struggled defining all variables and modalities due to the diversity of configurations beyond the current French energy market.

In conclusion this work establishes a structured foundation for early-stage design-space mapping of RE integration in social housing, supporting knowledge discovery and informed decision-making. Future research will investigate how Desing Space Exploration and Design by Shopping paradigm can be operationalized through proposed morphological chart, enabling exploration of alternative configurations and strengthen collaborative design processes in complex energy transition contexts.

References

Abi Akle, A., Yannou, B., & Minel, S. (2019). Information visualisation for efficient knowledge discovery and informed decision in design by shopping. *Journal of Engineering Design*, 30, 227–253. https://doi.org/10.1080/09544828.2019.1623383

Aparicio-Ruiz, P., Guadix-Martín, J., Barbadilla-Martín, E., & Muñuzuri-Sanz, J. (2019). Applying Renewable Energy Technologies in an Integrated Optimization Method for Residential Building's Design. *Applied Sciences*, 9(3), Article 3. https://doi.org/10.3390/app9030453

Aruta, G., Ascione, F., Bianco, N., Iovane, T., Mastellone, M., & Maria Mauro, G. (2023). Optimizing the energy transition of social housing to renewable nearly zero-energy community: The goal of sustainability. *Energy and Buildings*, 282, 112798. https://doi.org/10.1016/j.enbuild.2023.112798

Balling, R. (1999). Design by Shopping: A New Paradigm. *Proceedings of the Third World Congress of Structural and Multidisciplinary Optimization*, 1, 295–297.

https://doi.org/10.1017/pds.2026.10414 Published online by Cambridge University Press

Boeijen, A., Daalhuizen, J., Zijlstra, J., & van der Schoor, R. (2013). *Delft Design Guide : Design strategies and methods*. BIS Publishers. http://www.bispublishers.com/delft-design-guide.html
Castañeda, K., Herrera, R. F., Sanchez Rivera, O., & Mejia-Aguilar, G. (2023). Set-Based Design in Construction Projects: Benefits, Difficulties and Trends. https://doi.org/10.24928/2023/0197
Conrad, L. Y., & Tucker, V. M. (2018). Making it tangible: Hybrid card sorting within qualitative interviews. *Journal of Documentation*, 75(2), 397–416. https://doi.org/10.1108/JD-06-2018-0091
Dabush, I., Cohen, C., Pearlmutter, D., Schwartz, M., & Halfon, E. (2023). Economic and social utility of installing photovoltaic systems on affordable-housing rooftops: A model based on the game-theory approach. *Building and Environment*, 228, 109835. https://doi.org/10.1016/j.buildenv.2022.109835
De Luca, G., Ballarini, I., Lorenzati, A., & Corrado, V. (2020). Renovation of a social house into a NZEB: Use of renewable energy sources and economic implications. *Renewable Energy*, 159, 356–370. https://doi.org/10.1016/j.renene.2020.05.170
Hannapel, S., & Vlahopoulos, N. (2014). Implementation of set-based design in multidisciplinary design optimization. *Structural and Multidisciplinary Optimization*, 50(1), 101–112. https://doi.org/10.1007/s00158-013-1034-2
Hülagü, R. (2024). *Morphological chart as a tool for analysis: A study on structural solutions, design types and disciplinary mindsets in design education*. http://hdl.handle.net/11527/25926
Karunathilake, H., Hewage, K., Brinkerhoff, J., & Sadiq, R. (2019). Optimal renewable energy supply choices for net-zero ready buildings: A life cycle thinking approach under uncertainty. *Energy and Buildings*, 201, 70–89. https://doi.org/10.1016/j.enbuild.2019.07.030
McCabe, A., Pojani, D., & van Groenou, A. B. (2018). The application of renewable energy to social housing : A systematic review. *Energy Policy*, 114, 549–557. https://doi.org/10.1016/j.enpol.2017.12.031
Moore, N., Haines, V., & Lilley, D. (2015). Improving the installation of renewable heating technology in UK social housing properties through user centred design. *Indoor and Built Environment*, 24(7), 970–985. https://doi.org/10.1177/1420326X15598819
Muyingo, H. (2015). Organizational Challenges in the Adoption of Building Applied Photovoltaics in the Swedish Tenant-Owner Housing Sector. *Sustainability*, 7(4), Article 4. https://doi.org/10.3390/su7043637
Parreño-Rodriguez, A., Ramallo-Gonzalez, A., Chinchilla, M., & Molina-Garcia, Á. (2023). Community Energy Solutions for Addressing Energy Poverty : A Local Case Study in Spain. *Energy and Buildings*, 296, 113418. https://doi.org/10.1016/j.enbuild.2023.113418
Pugh, S. (1991). *Total design : Integrated methods for successful product engineering*. Addison-Wesley. https://cir.nii.ac.jp/crid/1971149384786846727
Raudberget, D. (2011). Enabling Set-Based Concurrent Engineering in traditional product development. In *Proceedings of the 18th International Conference on Engineering Design*, ICED 11 (Vol. 1).
Ritchey, T. (2014). *General Morphological Analysis – A general method for non-quantified modelling*. Swedish Morphological Society.
Seabra, B., Pereira, P. F., Corvacho, H., Pires, C., & Ramos, N. M. M. (2021). Low Energy Renovation of Social Housing : Recommendations on Monitoring and Renewable Energies Use. *Sustainability*, 13(5), 2718. https://doi.org/10.3390/su13052718
Smith, G., Richardson, J., Summers, J., & Mocko, G. (2012). Concept Exploration Through Morphological Charts : An Experimental Study. *Journal of Mechanical Design.* https://doi.org/10.1115/1.4006261
Toche, B., Pellerin, R., & Fortin, C. (2020). Set-based design : A review and new directions. *Design Science*, 6, e18. https://doi.org/10.1017/dsj.2020.16
Vallati, A., Fiorini, C. V., Muzi, F., & di Matteo, M. (2023). Energy simulation scenario to social housing building : Combining heat pump and renewable energy system. *2023 8th International Conference on Smart and Sustainable Technologies (SpliTech)*, 1–5. https://doi.org/10.23919/SpliTech58164.2023.10193241
Wheelwright, S. C., & Clark, K. B. (1992). *Revolutionizing Product Development : Quantum Leaps in Speed, Efficiency, and Quality*. Simon and Schuste.
Yin, R. K. (2014). *Case Study Research*. SAGE Publications.
Zeiler, W. (2018). Morphology in conceptual building design. *Technological Forecasting and Social Change*, 126, 102–115. https://doi.org/10.1016/j.techfore.2017.06.012
Zimmermann, T. (2016). Card-sorting: From text to themes. In *Perspectives on data science for software engineering* (pp. 137–141). https://doi.org/10.1016/B978-0-12-804206-9.00027-1
Zwicky, F. (1967). The Morphological Approach to Discovery, Invention, Research and Construction. In *New Methods of Thought and Procedure* (p. 273–297). Springer. https://doi.org/10.1007/978-3-642-87617-2_14

https://doi.org/10.1017/pds.2026.10414 Published online by Cambridge University Press