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Are we really future-proofing our high energy performance buildings? Energy renovations in a context of techno-economic, political and social uncertainty

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ABSTRACT

Increasing the energy performance of buildings is an essential cornerstone in the transition to a more sustainable building sector. Nearly Zero Energy Buildings (NZEBs) are imposed by European regulations and in recent years there has been increased attention to related concepts, grouped under “High Energy Performance Buildings” (HEPBs) by frontrunners in the sector. The study of the performance level of these buildings during the design phase is often limited to a linear and relatively static analysis of the net energy demand, the related CO2 emissions and energy cost in which the study period is usually one single, typical year for which present-day data on energy cost and CO_2-emissions is used. In this manner, the potential in the social, ecological and economic field, especially for energetic building renovations, could be partially or completely missed. Research is lacking on design approaches with a long-term vision for the wider perspective of sustainable and resilient development in the long term. Failing to consider uncertainties and risks in boundary conditions (such as changes in energy and investment costs, participation, technological progress, etc.) when deciding on energy renovation measures can have major consequences for the short-term and long-term performance of the buildings and its environment at various scales. For example, if market conditions are not in favour of the building owners, sub-optimal renovation measures may have major socio-economic consequences. This paper studies the concepts of future-proofing and the parameters that are related to uncertainties and risks in improved energy optimisation assessments for residential buildings towards the positive energy balance. The influence of future-proofing attempts on the performance effectiveness is furthermore tested. Design strategies that, according to literature, make energetic renovations more future-proof, explicitly require further (sequential) case-specific research and are discussed and illustrated by means of practical examples.

Introduction

According to the IPCC, buildings have the greatest potential for long-term, cost-effective GHG emission reductions of all major emitting sectors (IPCC 2007; 2022b). It would take at least half a half-century to replace all existing entirely with new, more sustainable buildings. This intervention would furthermore be resource intensive and lead to a strong increase in embodied energy and carbon emissions. Refurbishment of the existing building stock is therefore a key priority in the years to come (Paduart 2012; Georgiadou, Hacking, and Guthrie

2012; European Environmental Agency (EEA) 2022; European Commission 2022). There is furthermore a growing awareness of the enormous waste streams, generated by the construction industry and the higher embodied energy and carbon emissions that are often associated with new constructions (IPCC 2007; 2022b). Deep energetic renovations are for most households a complex action with wide-ranging financial consequences. This results in a slow turnover (sometimes referred to as the inertia) of the building stock, which demands decision makers of building design or renovation measures to implement long-term thinking.

The environment in which buildings operate is turbulent, resulting from radical shifts in for instance institutional frameworks, political and economic discontinuities, rise in environmental concerns and social activism, but also technological changes and innovations, etc. (Van Staden and Musco 2010). Bearing requested future trends in mind, our building stock will probably be constrained by dynamics of ever-changing conditions during its lifecycle. Such developments clearly induce the risk to limit the effectiveness of traditional planning strategies (Floricel and Miller 2001). Energetic renovating therefore includes overcoming spatial and temporal myopia and making decisions for the future (Verbruggen et al. 2011). In traditional energetic renovation strategies towards high energy performance buildings (HEPBs), the context in which the building will operate is however often assumed to be more or less constant, characterized by present-day constraints and present trends that are at best extrapolated into the future (Floricel and Miller 2001). These traditional approaches usually aim at updating to current standards by adding the best available measures (e.g. technology options) of today. However, are these solutions necessary the most suitable solutions and will they not cause problems in the future (e.g. rapidly becoming obsolete or underperforming)? Neglecting the influence and dynamics of uncertainties and risks for energy renovation decisions and other design decisions towards HEPBs (such as (net) Zero/Positive Energy Buildings), may result in suboptimal levels of the overall energetic renovation. This would conflict with sustainable development targets, e.g. as pointed out in 2010 by the United Nations, stating that: "*From today, each new building constructed in an energy-wasting manner or retrofitted to a suboptimal level will lock us into a high energy- and carbon-footprint future."*(UN Department of Economic and Social Affairs- Division for Sustainable Development Policy Analysis and Network Branch 2010). Therefore, this article tests the hypothesis that the future context in which building investments will operate should be looked into when deciding for them in order to guarantee future-proofing.

This article starts from the basic principles of future-proofing, with particular attention to Doubts about the Future (DaF) that are inherent to building (renovation) projects. Basic principles are then used to verify the current perception of "future-proofing" and "increasing robustness" of HEPBs in literature and the impact of considering DaF on the performance of HEPBs, compared to traditional approaches in the design process. The paper subsequently explores design approaches that are currently believed to be suitable for future-proofing and increasing robustness, applicable in the research of suitable energy technology interventions that affect energy demand, local energy production and energy storage profiles of buildings towards HEPBs.

1. Basic principles of future-proofing HEPBs

While the construction sector is rethinking its design and construction practices towards increased future-proofing in an ever evolving context (Merrild, Guldager Jensen, and John 2016), there is no consensus yet on what future-proofing actually entails. The risk of steering towards reduced improvements and creating lock-in effects may therefore still exist, even when a project is declared "future-proof" or variants thereof. "Future-proof" as well as "robust" are often seen as synonyms and associated with dealing DaF. Rehman and Ryan (2015) defined "robustness" as the building's ability to perform without failure under adversity, thereby increasing immunity to uncontrollable environmental fluctuations (inspired by Taguchi's approach to quality by design (Taguchi 1986)). The assumption that disruptive events can fully be managed by planning and forecasting is not valid (Horton 2012). Because of possible ambiguity or current ignorance about future events (unknown unknowns), not only during the full building's lifecycle, but also during the service life of energy technology options and other energy-efficiency measures, it is appropriate to prepare for a future that is very different than what could have been predicted by means of forecasts (Georgiadou, Hacking, and Guthrie 2012). Future-proofing refers to strategically planning and aiming to mitigate adversity and disruptions, inherent to long-term decisions, while taking advantage of future opportunities by combining robustness with governability (Kohler and Moffatt 2003; Howlett, Maleviti, and Hacking 2012) (as is reflected in Figure 1). Thereby it is anticipated that the buildings will not be constrained in future contexts (Rehman and Ryan 2015). Future-proofing allows to represent a point of departure from which to develop the future-proof concept further (CIBSE 2005; Verbruggen, Marchohi, and Janssens 2011). The definition of sustainability, can -according to the Brundtland Commission- be defined as “a development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development 1987). From this rather broad definition, it can be argued that “future-proofing” our interventions to improve the energy performance of buildings, is a key ingredient in obtaining a more sustainable status (Visser and Brundtland 2013; Jewell et al. 2010). Future-proofing is thereby underpinned by European and national roadmaps with milestones and domestic progress indicators (EUR-lex 2019), which emphasises the need for clear alignment of “future-proof” concepts.

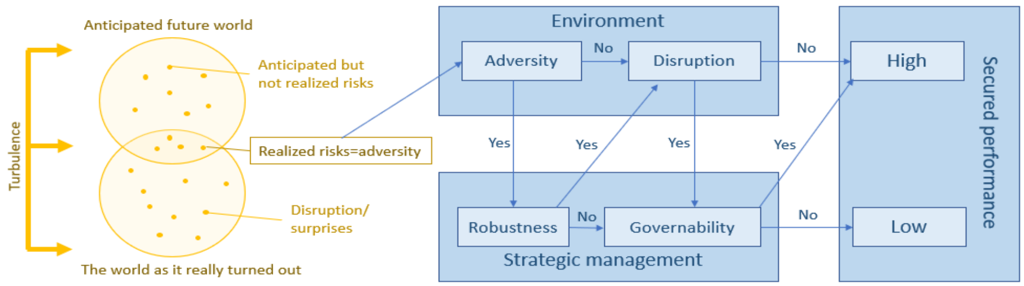

Figure 1: For future-proofing, both robustness and governability are needed (adapted from (Floricel and Miller 2001)*).*

Turbulence by surprises, ignorance, uncertainty and anticipatory risks are in this article compiled under “DaF” and may create disruption and aversity in the assumed boundary conditions under which HEPBs are designed, constructed, operate, renovated, etc. DaF can be categorized in three distinct groups: risks, uncertainties and ignorance. The term “uncertainties” and “risks” both refer to a possible future outcomes but are in fact not the same. (Anticipatory) “risks” refer to situations where probabilities can be assigned (forecasting are suitable approaches for risk management). Contrary to risk management, “uncertainty” and “ignorance” entail the occurrence of surprises (Floricel and Miller 2001; Georgiadou, Hacking, and Guthrie 2012; Szigeti et al. 2011; Verbruggen et al. 2011). Probabilities can neither be assigned to “ignorance” and “uncertainties”, nor can it be forecasted, which is deeply problematic in feasibility studies (Verbruggen et al. 2011; Stirling et al. 1999).

In this article we have looked to further categorize DaF. Two prominent groups include epistemic and aleatory turbulence (an overview is given in Figure 2). The epistemic turbulence refers to potential deficiencies that are caused by a lack of knowledge (e.g. simplification of physical processes in dynamic building simulation tools) (Iaccarino 2009). Aleatory turbulence arises from inherently random or variable nature of a quantity and the system on which it is based (Rastogi 2016). In (IEC 1990), a third category is discussed: errors, defined as the difference between observed or measured value or condition and the true, actual value or condition. Turbulence with regards to the reliability of systems (e.g. failure of a system) is added. In sensitivity analyses, the epistemic turbulence, system reliability and errors are expected to become more insignificant (e.g. by calibration with observations, improving numerical models and providing better, more detailed information, using prefabricated and pre-assembled construction elements, more accurate measuring instruments, etc.) (C.J. Hopfe 2009). The aleatory turbulence is however irreducible, it cannot easily be eliminated, because of its inherent randomness and natural variability (Moazami et al. 2019). This therefore calls for governability in the HEPB-designs. In (Cheng et al. 2017; Carey and Burgman 2008) two more categories of turbulence are added: linguistic and decision. Decision turbulence is linked to the cognitive biases on energy decisions in buildings. Understanding of such cognitive biases, can augment future research that include technology adoption (or the spread of new technologies), social and environmental psychology (that introduces understanding of values, attitudes and norms on designer's energy decisions) and social constructions (understanding of energy use that is embedded in routine behaviour) (Klotz 2011). Linguistic turbulence causes miscommunication and may for instance result in arbitrary disagreement. This once again invites to look into the concept and understanding of "future-proofing" in literature.

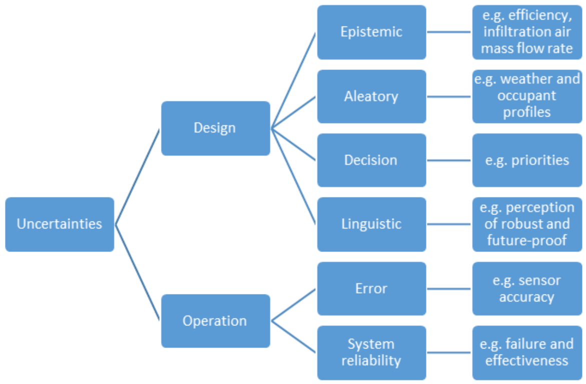

Figure 2: Types of DaF in a HEPB-context (based on (Cheng et al. 2017; Carey and Burgman 2008)*).*

DaF are spread across different domains and can range widely, which threatens to lead to a loss of overview and insufficient inclusion in design methodologies (sometimes even intentionally neglected because of complexity (Georgiadou, Hacking, and Guthrie 2012)). Sources of DaF can however be collected and categorized by domain, using the Social, Technological, Economic, Environmental and Political (STEEP). In Table 1, such an overview of possible drivers for DaF is given, collected from (Georgiadou, Hacking, and Guthrie 2012; Szigeti et al. 2011) in a STEEP framework and supplemented by drivers that were found throughout the rest of this literature review.

Table 1: STEEP framework with drivers for DaF that affect the energy performance of HEPBs (adapted from (Georgiadou, Hacking, and Guthrie 2012; Szigeti et al. 2011)*).*

Social	a)	Lifestyle changes (housing unit types, occupant behaviour schemes, new working and living patterns, energy poverty, etc.)
	b)	Demographic changes (age, gender, race, household sizes, privacy protection issues etc.)
Technological	c)	(Maturity of) innovations (novel energy efficiency measures, RES, construction practices, accuracy in energy consumption data, etc.)
	d)	Durability (frequency of repair, maintenance, accessibility, building management, construction quality, etc.)
	e)	New manners of collaboration (e.g. energy communities, privacy protection, etc.)
Economic	f)	Energy prices and energy tariff structures
	g)	Scarcity of non-renewable energy resources
	h)	Technology prices (RES, storage, etc.)
	i)	Revenue models (e.g. performance contracting, etc.)
	j)	Economic downturn (e.g. being influenced by taxation changes)
Environmental	k)	Climate change (hotter and drier summers, overheating, urban heat island effect, etc.)
	l)	Market and customer values towards environment (e.g. engagement towards the environment)
Political	m)	Funding (grants, initiatives, etc.)
	n)	Trading policies
	o)	Energy security
	p)	Energy and environmental targets (e.g. resulting in building regulations and standards)

2. What is considered robust and future-proof?

This section examines the extent to which the concepts of Chapter 1 are considered in practice, more specifically, for future-proofing (mostly energy) renovation decisions. Discovery Service and Google Scholar were used as a bibliographic databases to test the current perception on robustness and future-proofing in literature.

The screening has been conducted by combining keywords form the following two groups: (i) robustness, future-proof, uncertainty and (ii) zero energy building, high performance buildings, low energy building, building energy renovation and similar ones to find out what is perceived as "robust", "future-proof" and derivates in literature. Insights from Chapter 1 of this paper were used as the basis for an assessment matrix. The 33 retained sources had the form of journal and conference papers, books, reports and guidelines and are presented in Figure 3. This analysis indicated three general categories of approaches to deal with DaF in the design and renovation decisions towards HEPBs, ranked following increased future-proof levels:

(1) Straightforward, business-as-usual approaches towards robust HEPBs, involve rather conventional and narrowly-focused energy efficiency measures. Cost-effectiveness is an important driver in such approaches. These buildings demonstrate a somewhat limited attempt at future-proofing. Low-hanging fruit or readily available measures are typically used to increase performance levels of these buildings. The time-dimension in the analysis is usually limited to the operational phase, e.g. aiming at short-payback periods (such as PV panels in a context with feed-in tariffs or other financial incentives). In such approaches future trends are almost completely neglected (e.g. (Bragança, Vieira, and Andrade 2014)).
(2) A second category of approaches are risks- and uncertainty-oriented and consider operational performance over several years, taking into account future trends of a limited set of categories of uncertainties (e.g. Table 1). Depending on the subject of the study (e.g. climate robustness for a zero energy building), uncertainties are taken into account in linear or sequential, static or dynamic feasibility studies. Such approaches usually result in strategies where: (i) short-term reduction of the performance gap between predicted and real performance is pursued (often applied in projects in which soft-landings are planned (e.g. extending responsibility of the design team, collaboration with end-users, etc.)),(ii) were specific (often statistical) mid- and long term robustness regarding a limited number of uncertainties (usually only occupant behaviour and climate change) is pursued.
(3) More extensive future-oriented approaches usually surpass our current policy framework and demonstrate governability (e.g. adaptability) to a future context. These approaches often dynamically explore an extensive set of expected futures, including a variety of sources of uncertainty. Such future-proof designs not only take into consideration what is implemented tomorrow, but also what is to be added in further retrofits in the long-term. The corresponding designs will therefore inter alia make provisions for installation of available technologies, which are e.g. not yet financially feasible at the time of construction or partial retrofit (e.g. caused by high installation and investment costs or energy tariffs). Measures that are highly adaptive and flexible or simply straightforward to operate are frequently found to be suitable under such approaches (e.g. (Moazami et al. 2019)). In all cases studied, future-oriented approaches focus on dealing with long- term uncertainties. Such approaches are typically found in studies that focus on designing buildings that lend themselves for circularity (Vansco et al. 2018).

The pursuit of robustness and future-proofing in the selection of design and renovation measures for HEPBs is hampered by the lack of common understanding of these concepts (Georgiadou, Hacking, and Guthrie 2012). To assign the same "future-proof"-status, any of the three aforementioned approaches is applied in the examples of Figure 3, although they might in reality not all rank equally in terms of future-proofing (e.g. in (Ramon 2021; Georgiadou, Hacking and Guthrie 2012; Shen and Sun 2016) compared to (Moazami et al. 2019)). In some cases, a distinction is provided by emphasizing the source of DaF that are considered to declare the design a variant of "future-proof" (e.g. climate robustness in case the analysis was only performed under uncertainty of a changing climate). In an extension of this, it can also be suggested that claiming certain future-proof levels should always be combined with the declaration of the design objective(s) (Verhaeghe, Verbeke, and Audenaert 2021)), focusing on another deliverable may result in very different designs (e.g. carbon-robust versus comfort-robust). The keyword "uncertainty" identified most sources that led to robust results in the straightforward and uncertainty-oriented approaches. "Future-proofing", was the keyword that returned the largest number of

	Author(s)	(Coley, Kershaw, and Eames 2012)	(Nik, Mata and Sasic Kalagasidis 2015)	(Shen and Sun 2016)	(Galimshina, Moustapha and	(Yu, Chen and Sun 2016)	(Buckner, Lafrenie and Denommée 2016)	(Li and Wang 2021)	(Lu, Wang and Yan 2017)	(Huang, Huang, and Sun 2018)	(Hopfe 2009)	(Floricel and Miller 2001)	(Moazami, Salvatore and Vahid 2019)	(Galle, Poppe and Cambier 2019)	(Zhou, Cao, and Hensen 2021)	(Westermann and Evins 2021)	(Ji, Liang and Xei 2021)	(Wang, Qi and Ren 2021)
DaF	Social	a		a	a		a	a	a	a	a	x	a	a	a	a		a
	Technological				d,c		c			d,c		c		d	c,d,e			
	Economic				f,h	d	f,h					h			f,j		f	f
	Environmental	k	k	k	k	k	k	k	k	k	k	x	k			k		k
	Political											x					p	
Keyword/naming		Future-proof against higher temperatures	Robust against climate change	...under uncertainties	Robust	...under uncertainties	Future-proof	Risk-benefit-based	Robust	Robust	Robust	Robust, flexible	Climate-robust	Robust	Robust	Uncertainty-aware, robust	Uncertainty-based optimal	Uncertainty-based optimal
Type of source		Journal	Journal	Journal	Journal	Journal	Book	Journal	Journal	Journal	Book (PhD)	Journal	Journal	Report	Journal	Journal	Journal	Journal
With Case study		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X
Focus on	Epistemic			X				X	X	X	X	X				X	X	
	Aleatory	X	X		X	X	X	X	X	X	X	X	X	X	X			X
	Error											X						
	Linguistic																	
	Decisoin											X		X	X			
	ST/LT uncertainty	LT	LT	ST	LT	LT	LT	ST	ST/LT	ST/LT	ST/LT	LT	LT	LT	LT	ST	ST	LT
|Impact [%]|		/	≤78	≤14.4	≤30	≤20	/	≤40	≤45,6	≤13	≤75	/	≤14.4	/	≤77	≤30	≤71	≤14.2

	Author(s)	(Chang, Rivera, and Wanielista 2011)	(Li, Wang, and Tang 2019)	(Li and Wang 2020)	(Kotireddy, Hoes, and Hensen, 2017)	(Georgiadou, Hacking, and Guthrie 2012)	(Alavirad, Mohammadi and Hoes 2022)	(Kotireddy, Hoes, and Hensen 2018)	(Kotireddy, Hoes, and Hensen 2015)	(Rysanek and Choudhary 2013)	(Cheng, Wang and Yan 2017)	(Leyten and Kurvers 2006)	(Lu, Shengwei and Chengchu 2017)	(Ramon 2021)	(Howlett, Malewiti, and Hacking 2012)	(De Wilde 2014)	(Bean, Volt and Dorizas 2019)
DaF	Social		a	a	a	a,b	a	a	a	a	a		a		a	a	X
	Technological		d	d		c		x		c	c	d			c		X
	Economic	f				f,h		f		f,h				f			X
	Environmental	k	k	k	k	k	k	k	k	k	k		k	k	k	X	X
	Political					o,p		m		m					p		X
Keyword/naming		Uncertainty-based optimal	Robust	Robust	Robust	Future-proof, robust	Future-proof, robust	Robust	Robust	Robust, optimum under uncertainty	Uncertainty-based optimal	Robust		Future-proof, climate-robust, robust	Future-oriented, future-proof	Robust, occupant-proof, climate-change-proof, performance based buildings	Future-proof
Type of source		Journal	Journal	Journal	Conference	Journal	Journal	Journal	Conference	Journal	Journal	Journal	Journal	Book (PhD)	Journal	Journal	EPBD
With Case study		X	X	X	X		X	X	X	X	X		X	X		X	
Focus on	Epistemic	X	X	X							X	X	X			X	X
	Aleatory		X	X	X	X	X	X	X	X	X	X		X	X		X
	Error					X				X	X					X	
	Linguistic																
	Decisoin									X							X
	ST/LT uncertainty	ST	ST/LT	ST/LT	LT	LT	LT	LT	LT	LT	ST/LT	ST/LT	ST	LT	LT	ST	LT
|Impact [%]|		≤70	≤36.8	≤54	/	/	≤100	/	/	≤50	≤17,7	≤50	/	≤67	/	≤30	/

Figure 3: Analysis of the perception of future-proofing concepts for HEPBs based on case studies and recommendations in literature. (For explanation of each letter under the column "DaF" (Doubts about the Future), please refer to Table 1; x=mentioned in a generic manner, not specified; LT= Long-Term; ST= Short-term, |Impact [%]|describes the impact of considering DaF on the declared performance (in terms of energy demand, life cycle cost, probability of achieving an annual zero energy balance, etc., "/" if not quantified)).

covered categories of uncertainties within one project (e.g. (Alavirad, Mohammadi and Hoes 2022)). In most cases “future-proofing” at least contained preparing for changes in environmental policies. However, exceptions to this are found (e.g. in (Nik, Mata, and Sasic Kalagasidis 2015)). Climate robustness was found to be most popular when aiming at future-proofing. A possible explanation is that governments started to promote climate change adaptation measures to reduce the building stock’s vulnerability to climate change (Georgiadou, Hacking, and Guthrie 2012; IPCC 2022a). Future-proofing is in all cases a target, however, was never really completely attained, which was not reflected in the "future-proof" designation of the project. In many cases, but not in all, robustness refers to “statistically robust” (Leyten and Kurvers 2006). The declared performance level in the studies depends on the objectives (energy demand, energy cost, probability of achieving an annual zero energy balance, etc.) and the methodology that was considered to select appropriate measures. Therefore, the reported impact on the performance level in Figure 3 cannot be compared directly between the cases. However, the general consensus among the sources is that DaF have a significant impact on performance levels. Up to 100% variance in performance level by introducing DaF was found in the selected cases, which stresses the importance of considering future-proofing in feasibility studies towards HEPBs (as was confirmed in other sources, e.g. (Djunaedy et al. 2011; Alavirad et al. 2022; Z. Zhou et al. 2016; Verbruggen et al. 2011; Weitzman 1998)). Even though looking into the (far) distant future still remains delicate (Verbruggen et al. 2011), (Weitzman 1998; Verbruggen et al. 2011) found that it is recommended to consider DaF under which the buildings operate when deciding for energy renovation measures, as it is more effective than taking a blind chance.

3. Future-proof energy design and renovation ingredients

With this chapter, it is not the authors’ intention to provide one-fits-all interpretations of qualitative approaches as the future-proofing capacity can building-dependent. Marginal deviation may for instance be caused by differences in e.g. thermal mass, geographical variance such as weather conditions, occupant behaviour, the basis on which requirements for increased future-proofing are defined, etc. (Alavirad et al. 2022). Instead, this chapter aims at increasing understanding of “future-proofing”, providing practical (pre-)design inspiration for possible energetic renovation measures (with focus on energy technology options) and avoiding lingering in the status-quo of conventional energetic renovation options (e.g. increasing insulation thickness and performance of technical equipment). Distinction is made between the pre-design (design goals) and the design (design means), conform (Howlett, Maleviti, and Hacking 2012). Pre-design considerations describe the relation between HEPB-projects and its environment and provide the framework/vision for the project design. These inter alia include considerations that relate to the site selection (e.g. connection to the energy hinterland, proximity to infrastructure, opportunities for synergies with the neighbouring buildings such as shared installations, mixed-use communities, influenced by diversity, etc.). It also includes the ability of the building to accommodate future contextual changes (e.g. climate-ready, adaptive to changes in the energy hinterland and neighbouring buildings, technologic improvements, legislation, etc.) and social considerations, such as encouragement of active and regular collective maintenance, foundations for energy partnerships, etc. When

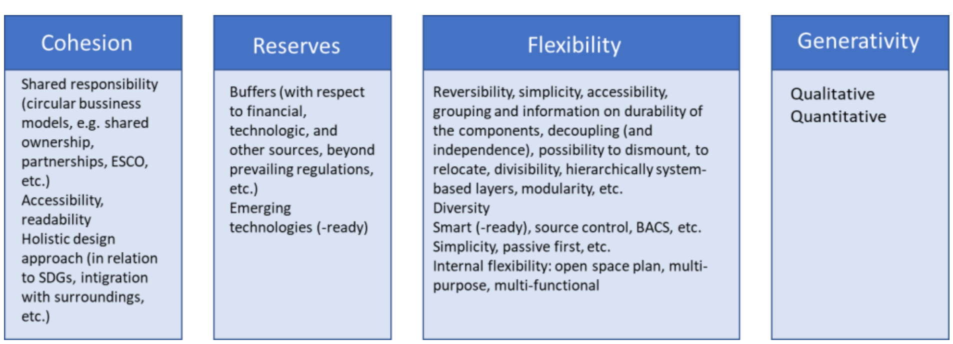

Figure 4: Interpretation of future-proof and robust design and renovation considerations (based on (Howlett, Maleviti, and Hacking 2012; Georgiadou, Hacking, and Guthrie 2012; Nakib 2010; Leyten and Kurvers 2006b))

dealing with DaF in a qualitative manner, popular design strategies can be grouped under four main drivers that are presented in Figure 4 and described below: (i) cohesion, (ii) reserves and oversizing, (iii) flexibility and (iv) generativity. **Error! Reference source not found.**

3.1. Cohesion

Cohesion as a driver is focused on avoidance of disintegration (Floricel and Miller 2001). It includes detailed delineation of responsibilities for each party and performance conditions in a time-perspective e.g. ensured through price, transfer, penalty, incentives and other contractual clauses. More examples can be found in (Copper 2020; Collectief 2020). Disintegration can also be viewed from a physical perspective. According to the S. Brand model, layers should be divided, based on its life span (as is reflected in other, similar models as well (Schmidt and Austin 2016; Rockow, Ross, and Black 2019)). In addition, (Leyten and Kurvers 2006) argue that when technical systems with different functionality, such as heating and ventilation, work as an integrated system, they are typically more prone to underperform (explicitly with regards to comfort levels) during the building's service life, resulting in decreased future-proofing of the design choices. An example is decreasing the air supply of an induction unit to prevent draught and thereby unwillingly decreasing heating or cooling capacity, which then results in lower future-proofing. Designing these layers to operate independent and to organize and separate them hierarchically according life span and functionality, reduces the intervention size (e.g. avoiding large interventions in all layers, including those that could have sustained) (Seuntjens et al. 2022; Nakib 2010). Supplementing guidelines often cover flexibility (which is explained in Chapter 4.3). The scope of a HEPB project, is usually done on the basis of the balance metric (e.g. primary energy). Some of these (especially energy-dependent) balance metrics are obtained through weighting systems (e.g. primary energy factors (PEFs)) (Verhaeghe, Verbeke, and Audenaert 2021; Sartori, Napolitano, and Voss 2012; European Union 2012; Santos, Fagá, and Santos 2013; Berardi 2013). These weighting systems might evolve throughout the buildings' lifecycle, causing deviation from the design objectives. Therefore, a special form of cohesion relates to selecting unchanging, fact-based design objectives (e.g. by invariability and uniformity in definitions and assessment methodologies). Avoiding the need to use conversion factors for the assessment of future-proofing levels could thereby increase theoretical future-proofing of the measures. This must however be done with care, as it could mean leaving out essential information with regards to sustainability (e.g. if only final energy demand is considered, the impact of the difference in performance at production level is completely omitted).

3.2. Oversizing

By oversizing or creating reserves of financial, spatial and other resources and by outperforming statutory minima, a project could anticipate the uncertain future (Howlett, Maleviti, and Hacking 2012; Nakib 2010; Georgiadou, Hacking, and Guthrie 2012). It can furthermore translate in creating capacity for adaptability, e.g. by oversizing flow rates (Seuntjens et al. 2022) or providing more than the minimum spatial areas. Multi-purpose zones or "buffer zones", allow for the absorption of the overflow that is caused by change (Nakib 2010). A specific example was the requirement to provide 1,5m² extra storage room in social housing units, to allow installation of a solar water heater or heat pump with buffer tank in the future in Flemish social housing dwellings (Vlaamse Maatschappij voor Sociaal Wonen 2020). By oversizing and providing flexibility (described in Chapter 4.3), delayed interventions are possible (e.g. leaving space or financial means to insert certain measures or extensions in the future, when suitable boundary conditions are in place) (Verbruggen et al. 2011). Oversizing in general can be criticized as it may lead to higher energy and material consumption. Energy efficiency measures are almost all a highly irrevocable allocation of resources, as it takes additional measures that are sometimes prohibitive and insufficient in amount to make adaptations in the future (Verbruggen et al. 2011). Therefore, depending on how the quantitative analysis is conducted to determine the performance level (e.g. considering the full-life cycle or less than the service life of the measures), oversizing can result in a decreased performance level, e.g. when undoing efforts are disregarded. This irrevocability of investment decisions can be categorized in five categories: very strong, strong, medium, weak and reversal. In line with the conception in (Verbruggen et al. 2011), "very strong" refers to undoing efforts increasing over time, "strong" is when these efforts decay over time but remain above the reference of the initial effort, "medium" refers to higher undoing efforts than the initial effort at the beginning but fall below the initial effort and "weak" refers to undoing efforts are equal or lower than the initial cost. Investments with weak irrevocability are preferred over higher categories. Oversizing can in that sense contribute to reducing irrevocability, especially when aiming at flexibility (see Chapter 4.3), as undoing efforts can be reduced (e.g. instead of replacing and investing in a new installation because it cannot deliver the required heating demand anymore after some time, the settings -i.e. flexibility- of the oversized installation can be adapted to match the demand).

3.3. Flexibility

Buildings that are designed to be adaptable to changes that occur during their life cycle, have potential to be more resilient to turbulence on the long-term, than buildings that are tailored to meet particular short-term needs (Howlett, Maleviti, and Hacking 2012). Flexibility has been argued to be essential in future-proofing and is defined as the ability to monitor change in the environment, conceptualise a response to it and reconfigure with minimal effort and impact (Floricel and Miller 2001). This results in drivers such as reversibility, simplicity, accessibility, keeping track of information on durability of the components, decoupling (and independence), possibility to dismount, to relocate, diversity, and smart distribution (OVAM 2015; Rehman and Ryan 2015; Nakib 2010). Technical services can for instance be designed in a modular, accessible manner so that it can easily be demounted and part of the installation can be altered (e.g. making adjustments to allow improvements or new configurations). The CBCI Living Lab consists for example of different large modules in which the technical installation is completely bundled and the unit is placed on the upper floor (AVS 2022). To allow such flexibility, design considerations such as strategically locating cables and ducts (backbone pathways), fixed service rooms pluggable connections, wireless systems, dropped ceilings, raised floors and central cores are additionally provided (Nakib 2010). Flexibility can also translate in smartness[1] and diversity. An example are high-density, mixed-use developments (as part of a mixed city approach), characterized by proximity, sharing community facilities, local supply, etc. (Howlett, Maleviti, and Hacking 2012) or a variety in renewable energy sources and storage options. Source control was mentioned in (Leyten and Kurvers 2006), allowing to adapt (or even remove) a source (e.g. by tweaking ventilation effectiveness, ventilation rates, etc.). Sensor based approaches, smart metering with advanced systems and control algorithms provide flexibility to the HEPBs (Verbeke et al. 2020). The capabilities of HEPBs, to adapt its operation, storage and generation to the needs of occupants and the grid, thereby improving energy efficiency and overall performance, furthermore becomes increasingly important (Bean et al. 2019; Kolokotsa 2017). Energy technology options are thereby on the other hand gaining in complexity and are as a result increasingly misunderstood and often insufficiently or poorly controlled by building occupants (Leyten and Kurvers 2006). As a result, there are, on the other hand, a number of projects that focus instead on transparency to increase flexibility by allowing it to be understood by laymen by just looking at it, thereby to notice it when the system is not functioning well and even to denote to a certain level what is wrong with it (Leaman and Bordass 1993; Leyten and Kurvers 2006). An example are operable instead of automated windows, which are transparent to most people, so that they can directly see it when it does not operate as expected, e.g. whether or not it is stuck (Leyten and Kurvers 2006). Opting for less technologically sophisticated solutions towards HEPBs, may seem like a step back, but could in some cases result in increased robustness (for which authors refer to the lo-tech versus hi-tech discussion) (Morrison 1983; Leyten and Kurvers 2006).

3.4. Generativity

Generativity, or response generation could bring creative responses to situations that appear hard to solve (Floricel and Miller 2001). Previous research has addressed that measures to increase the performance level of a building, should not be determined based on a single set of boundary conditions (e.g. one single

[1] The adaptation of energy profiles (production, consumption and storage) and responding to the changing needs of occupants, climate changes, innovations, policies, commercially available services, etc. are all categorized under a building (project)'s smartness (Verbeke et al. 2020).

macroeconomic report or exogenous case study), which has been confirmed in e.g. (Rysanek and Choudhary 2013). In (Georgiadou, Hacking, and Guthrie 2012) future-proofing is otherwise described as stress-testing building solutions against a range of possible futures (both predictable and uncertain), so that they remain fit for purpose, avoiding the need for disruptive and expensive renovation. Futures techniques are suitable approaches to accommodate DaF, exploring a spectrum of plausible futures, rather than forecasting (Abaza, Bisset, and Sadler 2004; Georgiadou, Hacking, and Guthrie 2012; Howlett, Maleviti, and Hacking 2012). Qualitative strategies such as method used by Galle (2019) and relational probing are tools that can be used for this purpose (De Bono 1999). For such techniques, the importance of creating 'rich media' is stressed, e.g. surveying potential opponents and critics of the project to uncover possible flaws and risks, thereby stimulating improved design and renovation concepts (Floricel and Miller 2001). In addition, there are also many quantitative approaches, which are for instance based on extensive datasets and computational models and consider long-term dynamics in STEEP-boundary conditions (e.g. (Y. Zhou, Cao, and Hensen 2021; Westermann and Evins 2021; Van Gelder, Janssen, and Roels 2014; C.J. Hopfe 2009; Yu et al. 2016; REflex 2022).

Generally, studies that aim at dealing quantitatively with DaF are grouped in two categories: linear and sequential approaches. In the linear approach, a first step is to model the future by assessing the performance (e.g. the net present values) for all combinations of actions and events (i.e. assessing a variance of investment alternatives, each under the occurrence of events that describe the DaF, if possible with a certain probability to it) and select an optimum (investment) decision (Verbruggen et al. 2011). A second step in the linear approach is applying a decision rule to select robust designs from large design spaces. Popular are the max-min method (using performance spread as a robustness indicator), the minimax regret method (using maximum performance regret as a robustness indicator) and the best-case worst-case method (using performance deviation as robustness indicator) (Kotireddy, Hoes, and Hensen 2017). The advantage of the linear approaches is that it allows to structure decision problems, thereby revealing new likely events and overlooked alternatives while revealing clusters of less interest. It however can give very wrong answers as an important shortcoming lays in assuming the bundle of future scenarios as once-through trajectories that start in year 0 (the year of the investment) and end in the year of decommissioning. This linear assumption that is made thereby does not reflect real life processes that are in fact sequential and alternate over time (Verbruggen et al. 2011). The sequential decision approach, e.g. the real options and/or the Bayesian approach (Grenadier et al. 2010), is therefore essential when aiming at ensuring flexibility of investments with a service life beyond 30 to 40 years. This approach is encouraged for shorter-term investments as well and allows to change and update decisions as new information/ boundary conditions are in place (e.g. because of technologic development, changes in energy tariff structures, etc.) (Verbruggen et al. 2011). The objective of a design approach towards HEPBs may only consider finding the "ideal" investment strategy. However, it can be of value to explore the wider decision space around this design objective, since there is a risk of finding only less-than-optimal choices in this narrow space of the design objective alone (e.g. due to biases or prior preferences that have been exhibited at the design -or decision stages) (Rysanek and Choudhary 2013).

Special attention must in all cases be paid to rebound effects such as increasing the consumption of fans by increasing the amount of inlets and outlets in the design to oversize and create flexibility, or decreased lifespan of more flexible alternatives (Seuntjens et al. 2022). Another example of such rebound effect is given in (Li and Wang 2021) where the risk is pointed out that placing great emphasis on making a building robust for various extreme operational conditions, could lead to unnecessarily high operational costs. It is therefore once again stressed that measures towards increased future proofing, must be checked for effectiveness, all the more as results can be case-specific. This research therefore provides inspiration for future-proof ingredients and thereby aims at providing fertile ground for further research towards future-proofed design and renovation strategies that accommodate explicitly full lifecycle perspectives and DaF.

4. Discussion and conclusion

Literature agrees that there is a significant impact on the performance of HEPBs associated with the omission of DaF in feasibility studies. This underlines the importance of verifying whether we are currently really future-proofing our HEPBs. 'Future-proof', 'robust' and variants of this terminology, are still quite trivial in literature because the requirements to be labelled as such can be very far apart. By means of this selection of literature on future-proofing concepts, it became clear that still no consensus is reached on the design requirements that must be met in order to be labelled future-proof, robust or derivates. As a result, it has become a buzzword that can be awarded to a design or renovation project without actually meeting predefined criteria. In general, future-proofing concepts are classified and described by at least involving a deviation from standard solutions by combining DaF in the analysis. One set of requirements and the selection procedure towards a future-proofing set of energetic renovation measures however, deviates much from another. Calculation methodologies are often insufficient to attribute a case a variant of "future-proof" terminology, although this has been done repeatedly. A lot of research to find optimal renovation solutions is conducted in a steady-state, deterministic context. However, (more dynamic and sequential) studies on future-proof performance optimization under DaF are still lagging behind (Galimshina et al. 2021). Future-proofing is an essential cornerstone in the transition towards a more sustainable built environment. This requires an integral approach in which an energy system is placed in the right uncertain context. Most investigated studies in Figure 3 furthermore do not target future-proofing for the entire HEPB on every scale (geographical location in the world to district level, to building level, component level, etc.), but mostly consider either the building envelope or else the energy systems (Li and Wang 2020). However, an integrated approach -even when only targeting a specific building layer- is called for as it has potential to further improve future-proofing. The latter also implies exploring outside of the boundaries of the design objectives in the selection of appropriate measures towards HEPBs to future-proof (Rysanek and Choudhary 2013). At present, and to the best author's knowledge, it is not yet possible to formulate rules of thumb that indicate a one-fits-all ideal set of measures, suitable for each case. Some future-proof measures are even contradictory (e.g. hi-tech versus lo-tech discussion). This again stressed the need to investigate further whether the "reported as effective future-proofing ingredients" actually contribute to that goal in each specific case. It translates in complex and time-consuming feasibility studies. Continued research on future-proofing approaches and further reduction of computational complexity and time is therefore necessary to facilitate the uptake of appropriate future-proof design considerations.

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