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Review and Mapping of Parameters for the Early Stage Design of Adaptive Building Technologies through Life Cycle Assessment Tools

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Abstract: Adaptive Building Technologies have opened up a growing field of architectural research aimed at improving the overall building performance, ensuring comfort while reducing operational energy consumption. Focusing on flexibility over short timeframes, these new technologies are however rarely designed within the broader frame of sustainability over their entire lifecycle. How sustainable these zero energy technologies really are is yet to be established. The purpose of the research is to develop a flexible easy-to-use Life Cycle Assessment (LCA) tool to support creative innovation and sustainable design choices in the early concept and design stages of Adaptive Building Technologies. This paper reports on the results of the first step of the research, providing a mapping in terms of structure and contents of the parameters involved in the design of these technologies. Addressed from a holistic point of view, the elements of the system were defined though a qualitative approach: relevant parameters were collected through document analysis, reviewing the state-of-the-art technology through online databases as ScienceDirect, Scopus, MDPI, ResearchGate, and organized according to hierarchy and relevance in the different life cycle stages. As a result, the paper identifies (1) relevant parameters defining the design of Adaptive Building Technologies; (2) materials, processes and concepts specific to the design of these technologies, as compared to conventional building technologies; (3) issues and knowledge gaps to enable successive research phases; (4) specific actions in each life cycle stage for designers and producers to optimize the design of the technology. The mapping graphically and hierarchically organizes the elements of the system within a flexible structure to be implemented and integrated over time, as the technology evolves, to support parametric design and enable alternative design concepts to arise within a cradle-to-cradle perspective.

Keywords: LCA; building technologies; adaptive; autoreactive; zero energy; systematic; mapping; sustainable architecture; design parameters

1. Introduction

Buildings are an important part of the human-made environment, impacting almost all aspects in people's daily lives. In 2018, more than half of the world's population lived in urban settlements and within the next 30 years the rate is expected to reach 68% [1]. Cities are expected to grow [2] and using our resources efficiently is therefore more important than ever in order to solve the sustainable development dilemma between energy consumption and urbanization [3]. The building industry has not been left untouched by the radical changes that digital technologies are bringing to society [4].

Combining the recent technical and economic accessibility of new technologies to non-specialized users [5,6] and the global efforts towards cutting CO_2 emissions [7], Adaptive Building Technologies has surfaced as a strongly growing field of study addressing energy efficiency in buildings [8–13].

Unfortunately, while technological ephemeralisation on one hand enables us to do increasingly more with less, it also speeds up the rate at which our products are considered obsolete becoming waste. Our buildings and products are still built to last for hundreds of years, outliving our present needs and impacting many generations to come [14,15]. In an economy where change is the only constant, to hold and to accumulate is an outdated mindset [16]: since the problem is temporary, so must the solution be. Therefore, unless we want our resources to end up in landfills, the building industry needs to introduce new consumption patterns and supply chains [17,18], where "design for longevity" assumes a new meaning in terms of adaptability on short and on long term within a resource-efficient circular-economy mindset.

1.1. Framework

The Sustainable Development Goals (SDGs), adopted by the United Nations General Assembly in September 2015 in response to the increasing concern about the long-term sustainability of human societies, provides at the moment the most important framework for addressing the global challenges and internationally coordinate development towards a sustainable future [19]. The SDGs embrace a large range of transdisciplinary topics on a global scale, involving actors in all fields and contexts within a circular economic perspective where climate change, economic and social development are inextricably linked. The goals identified are [19]: (1) end poverty; (2) zero hunger; (3) health and well-being; (4) quality education; (5) gender equality; (6) clean water and sanitation; (7) affordable clean energy; (8) decent work and economic growth; (9) industry, innovation and infrastructure; (10) reduce inequalities; (11) sustainable cities and communities; (12) responsible consumption and production; (13) climate action; (14) life below water; (15) life on land; (16) peace, justice and strong institutions; (17) partnerships for the goals.

Architectural and urban design are an occasion to facilitate access to basic services, benefit a broad range of economic sectors and activities, improve human health, innovate the way we live, consume and produce, and not least the way we generate energy—if properly enabled [20]. Twenty-four commonly accepted Sustainable Architecture Strategies (SAS) are listed, as classified by Sassi [14], showing the potential areas of impact on the SDGs (Figure 1). Directly impacted goals are highlighted in the figure. However, as the SDGs are inextricably linked to each other, all goals can be considered to receive also an indirect impact though benefits achieved in other SDGs.

Among these strategies, those addressing energy in buildings (t. and u.) are increasingly being researched and supported by governments [21–23]. This is because the buildings sector is known to be the largest energy-consuming sector, accounting for over one-third of final energy consumption and greenhouse gas (GHG) emissions globally [7,24]. It is in this context that Adaptive Building Technologies (ABTs) have become an emerging research topic, aiming to save on operational energy (OE) by upgrading energy-intensive building systems. As building technologies respond to a complex but limited range of environmental triggers, these systems aim to react autonomously as independent decentralized systems.

ABTs distinguish themselves from other technologies by integrating adaptive materials (AMs) that transform energy in different forms to achieve kinetic change, with the aim to improve the energy efficiency and user comfort in buildings [5]. Autoreactive (Ar) technologies are a specific type of unpowered ABT, that use exclusively latent unused energy in the environment, as wind, heat or humidity reacting at zero voltage input [6]. Examples include the Hygroscope Meteorosensitive Morphology [25], a climate responsive architecture morphology based on the dynamic behaviour of wood when exposed to moisture fluctuations. The surface opens and closes without any need for technical control or external energy supply. Using similar ground principles, the Strandbeest project [26] moves mechanical skeleton structures by transforming wind energy through a system of

plastic compartments and rods, pressurizing and pumping out air. Among other low-tech solutions, the façade of the Pittsburgh Children's Museum [27] is shaded by a screen made out of translucent plastic tiles fixed on their upper side rotating as the wind gusts pass by giving substance to the otherwise invisible turbulences. Adaptive Building Skins (ABS) are a common application of ABTs, that enable the flexibility of the building surfaces to react within the timeframes of the human activity cycle, ranging from systems adapting within seconds to seasonal adaptations [8,11,28].

SUSTAINABLE ARCHITECTURE STRATEGIES

EU SDGs	SITE LAND USE					COMMUNITY						HEALTH AND WELL BEING						MATERIALS						ENERGY			WATER		
	a. Compact cities	b. Reduce transport impacts	c. Harmony with nature	d. Local food production		e. Participation	f. Housing for all	g. Training and employment	h. Quality public spaces	i. Educate to sustainability		j. Comfort	k. Safe, healthy buidlings	l. Identity and independence	m. Restorative environments		n. Design for longevity	o. Waste as resource	p. Avoid resource depletion	q. Min manufacturing impacts	r. Min embodied energy	s. Min waste		t. Min need, max efficiency	u. Green energy sources		v. Min need, max efficiency	w. Alternative water sources	y. Reduce use of main drains
1	x			x		x	x	x		x				x	x			x	x	x		x		x	x		x	x	
2				x		x		x											x								x	x	
3	x	x	x	x		x	x		x	x		x	x	x	x					x		x			x		x	x	x
4	x					x		x		x																			
5	x	x				x	x	x	x	x				x	x												x	x	
6	x						x						x	x					x			x					x	x	x
7	x																	x	x		x	x		x	x				
8	x					x		x		x				x					x	x									
9	x	x		x				x	x	x				x			x	x	x	x	x	x		x	x		x	x	x
10	x	x	x	x		x	x	x	x	x		x	x	x	x		x	x	x	x		x		x	x		x	x	
11	x	x	x	x		x	x		x	x		x	x	x	x		x	x	x	x	x	x		x	x		x	x	x
12	x	x		x		x				x			x				x	x	x	x	x	x		x			x	x	x
13	x	x	x	x		x				x			x				x	x	x	x	x	x		x	x		x	x	x
14	x	x	x	x														x		x		x			x		x	x	x
15	x	x	x	x														x		x		x			x		x	x	x
16	x			x		x	x	x	x	x				x	x		x	x	x	x				x	x		x	x	
17				x		x	x	x		x				x				x	x	x	x	x		x	x		x	x	

Figure 1. Potential impact of Sustainable Architecture Strategies (SAS) [14] on the Sustainable Development Goals (SDGs) [19].

1.2. Gap

The drive to reduce energy consumption in buildings has mainly focused on reducing the operational energy (OE) consumption by massively integrating Nearly Zero-Energy Building (nZEB) technologies and systems [21], often at the expense of an increase in the embodied energy (EE) or embodied carbon (EC) in building systems [29]. Neglecting to design through a lifecycle perspective can however result in "problem-shifting", ending with spending more resources upfront than the ones saved through sustainability measures [30]. Although Life Cycle Assessments (LCA) are considered effective tools to support decision-making and control the sustainable design of products as well of more complex building systems [31,32], performing an LCA is often considered complex, time-consuming, and expensive in the building industry [33]. LCAs are, whenever required, performed in the final design stages or even after the construction [34–36] with significant environmental impacts [31,37]. This lack of integration of LCA in the design process is due to a number of challenges: the presence of multiple stakeholders, little design standardization of complex products with multiple functions [33,34], and the inherent complexity of LCAs that involves that the topic is usually addressed by specialists. As highlighted by a number of studies, LCA must be integrated in the building design process as soon as possible, already from the early design stages, by diffusing the use of flexible easy-to-use tools integrated with databases of up-to date digital data [34,37,38].

In the design of ABTs aspects other than OE efficiency and user comfort are rarely taken into consideration: this can be seen from the topics that the literature on ABT addresses (Appendix A Table A1). When compared to the Sustainable Architecture Strategies (SAS) (Figure 2) it appears that the current focus is set on topics that are typically enabled during the operational life of the systems (Community, Health and well-being, Energy), while strategic areas involving design decisions in the early and later phases of the life cycle are still mostly unexplored (Site and land use, Materials, Water). For ABTs to achieve their full sustainability potential, designers need to take more conscious sustainable design choices in the early concept and design stages of the technology, taking all strategic areas into account.

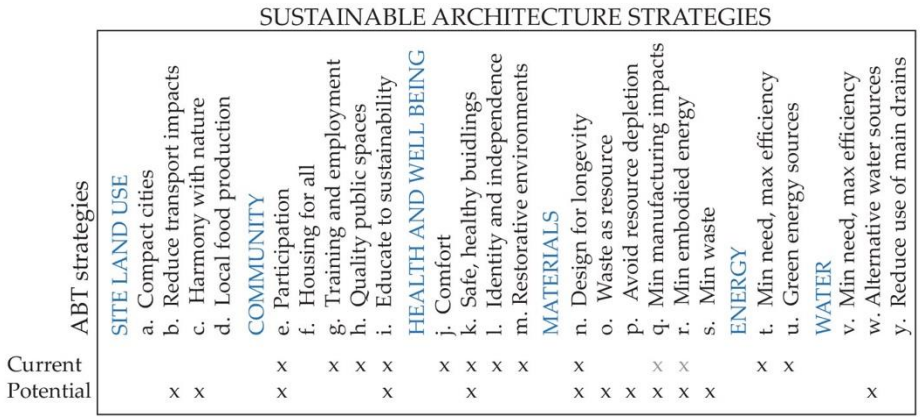

Figure 2. Current and potential impact strategies of Adaptive Building Technologies [5,8] within specific categories of the SAS [14].

The research addresses this gap by aiming to develop a flexible easy-to-use LCA tool to support the creative innovation and design of ABTs by proceeding through successive steps. This paper reports on the results of the first step of the research, providing a mapping structure of the parameters involved in the design of an ABT, to be further developed and integrated in successive research phases with additional information from databases and up-to date digital data.

1.3. Objectives

In order to allow the future development of an LCA tool specific for Adaptive Building Technologies (ABT), this paper aims to map within a hierarchical systematic structure, the parameters involved in the design of an ABT. To achieve this, a list of consecutive objectives has been identified:

1. A comprehensive review of the technologies, materials and systems involved in the design of Adaptive Building Technologies needs to be established, including present but also future development potentials. To be exhaustive, the review needs to approach technical aspects, as the potential and means of technological development, as well as arising sustainability issues, through a Life Cycle Thinking mindset.
2. Parameters that control the design and development of the technology need to be identified and organised into a hierarchical framework.
3. A straightforward way to build the LCA tool is to adapt the existing LCA tools assessing conventional building technologies to the specific case of assessing ABTs. Hence, the differences in method and content (materials, processes and concepts) that distinguish an Adaptive Building Technology's (ABT) Life Cycle Assessment (LCA) to that of conventional building technologies need to be identified.
4. To enable future improvements and evolution of the tool, current knowledge gaps need to be noted.

Figure 3 identifies the main areas of study: highlighted in dark blue, the phases where ABTs' LCA differs from a traditional LCA; and in light blue, those impacted by the design choices made in earlier life cycle stages.

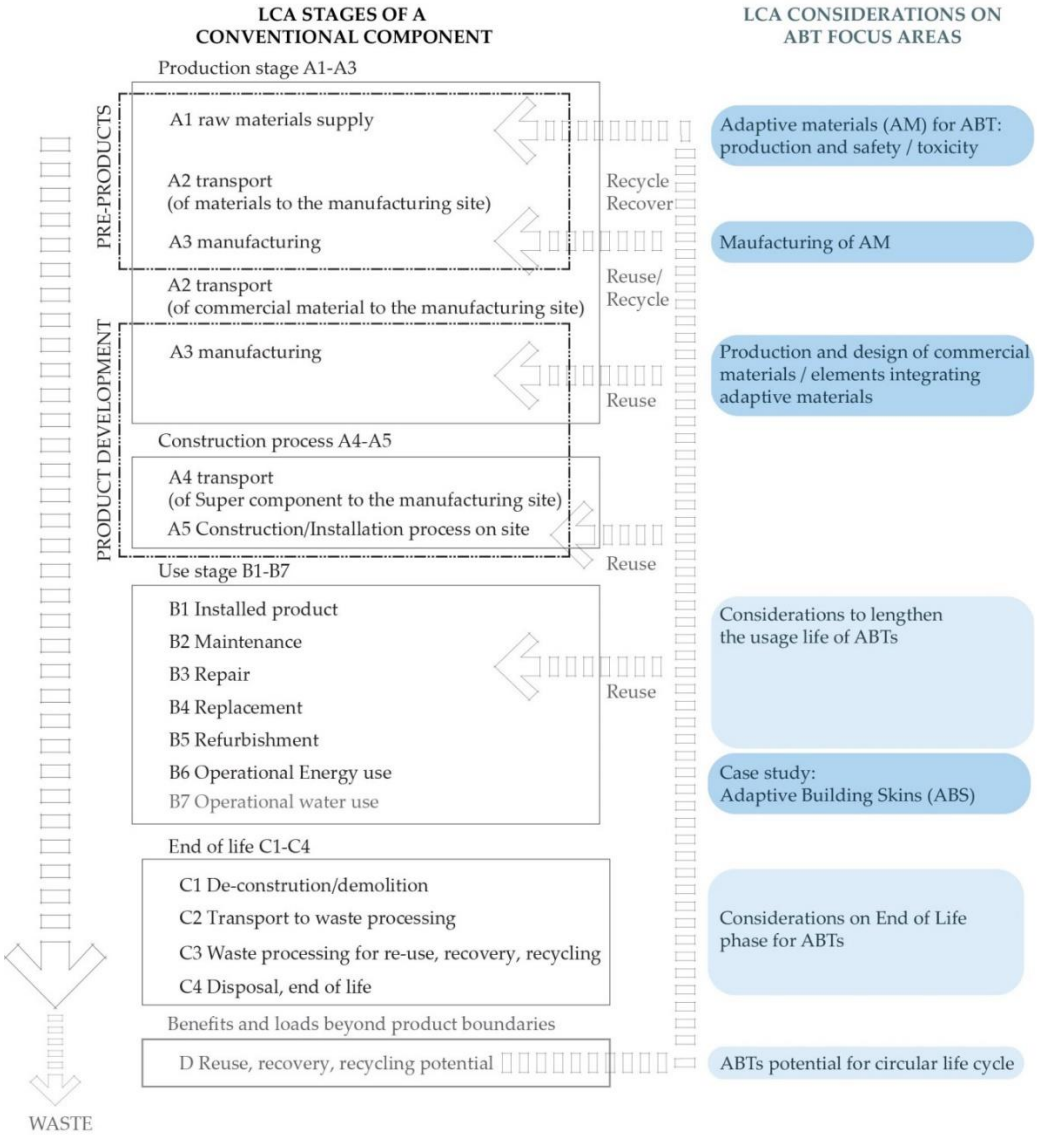

Figure 3. Life Cycle Assessment (LCA) phases of a conventional building component [39], and areas of focused study.

2. Materials and Methods

The mapping was developed in subsequent phases of research and analysis. The topic is addressed from a holistic point of view, defining though a qualitative research approach the elements of the system characterizing the LCA mapping of ABTs. ABT and LCA relevant parameters were collected through state-of-the-art document analysis and systematically organized according to hierarchy and relevance in the different LCA stages.

2.1. Background Research

Deepened research of the latest Adaptive Building Technologies was conducted through online available databases: ScienceDirect, Scopus, MDPI, ResearchGate, Science, Intech Open and through the university libraries of the authors' home universities.

Considering that ABT is a very young and still expanding field of study, the authors initially adopted broad research criteria in order to incorporate concepts and solutions from neighbouring fields of study. Therefore, both active and passive building systems were reviewed estimating their potential of technological upgrading through the integration of adaptive features. Databases were therefore searched using different combinations of a number of keywords, among which were "dynamic, reactive, active, adaptive, responsive, high-tech, low-tech, smart, behaviour, building system, façade, envelope, technology, material, architecture, design, LCA, life cycle, circular, sustainable", and expanded to the sources cited by the selected literature. The search was narrowed down to more recent publications, focusing on research and technologies achieved within the last 10 years (with the exception of one publication that seemed of specific relevance [40]), and especially on publications from 2017 and onwards. More detailed information of this search can be found in Table A2 (Appendix A).

The contents of the following literature review are summarised in Table A1 (Appendix A). As expected, the field of study addressing active and adaptive building envelopes appeared to be very dominant in the use of dynamic features in the architectural context. Active building systems include a very broad understanding of different kinds of powered control technologies with very different aims, from interactive installations [4] and climate-controlling systems [10,11]. By including very diverse types of systems, the review of the active building technologies allowed to take into consideration a broad variety of aspects, among which kinetic systems [41,42], computational networks and systems [43,44], energy-generating systems, solar cool facades [45], solar facades [46,47], Building Integrated Photovoltaics [48], and Piezoelectric surfaces [49]. These types of technologies were included in the review for their potential to be upgraded to Adaptive Building Technologies or function in combination with one. As the field of Adaptive Building Technologies is a young and growing field of study, a number of closely related concepts were grouped into the same "Adaptive" category, among which were Adaptive, Climate Adaptive, Kinetic and Autoreactive. Sources on Adaptive systems were found to report on the state-of-art of Adaptive technologies and materials [13,50], as well as their specific use in facades [51], while Climate Adaptive systems are exclusively focused on building skins [8,10]—with one more focused study on a specific material in use [12]. Similarly, Kinetic systems are also focused on an application in building envelopes [41,42]. Few available studies on specific adaptive technologies were also included, as PCM integrating technologies [52,53] and a shape-change technology [54]. Autoreactive systems appeared to be still a minority, although their development and use have been theorised both in terms of kinetics [5] and material technology [6,55]. Few solutions were also found to be realised as an upgrading of an existing building technology [56,57] and as a completely new façade-concept [58]. Another field of study that was found to use adaptive functional features is the field of industrial design. In this case however, the adaptive features were mainly used to achieve product desirability rather than sustainability. Hence, examples from the field of industrial design were not further deepened. Given the great amount of façade systems found in the review, two additional sources were added, to implement the background knowledge on common façade systems at the base for ABT integrations, and more specifically, on energy efficient building skins [59] and curtain wall [60]. Overall, of the 38 sources included in the review of Table A1 (Appendix A), seven reviewed the state-of-art of adaptive-relevant materials; 10 reviewed the state-of-art of relevant categories of technologies; four were material-specific; 12 technology-specific; two focused on the kinetic aspects; two on aspects of design development; one on the energy and comfort performance.

Pre-existing experiences and studies on the application of LCA as an early-stage design tools [37,38] were central to the development of the mapping concept. Aiming to focus on a specific technology under development, the background research however found LCA studies on adaptive technologies to be very few. Most LCA studies were found to refer mainly to buildings as a whole. Additional background information was therefore collected through sources in the form of reviews of LCA and environmental impacts of buildings [29,31] implemented with reviews of principles and calculation methods [35,61]. Areas of potential development, recurring issues and future challenges were identified both through a review [62] and reports on case-studies [33,35]. Sources discussing the use of available

simulation and design tools—mainly BIM [34], parametric [63] and evaluation frameworks [38]—set the base for identifying LCA design parameters on building scale. Finally, focused LCA parameters on product and material scale were identified through LCA studies on specific building components and materials. LCA studies on building components included a review of several hundred typical external wall solutions [64], an assessment of a dynamic component for the kinetic features [65], and a general framework for emerging technologies [66]. One study on facades was identified as relevant due to the use of dynamic simulations to investigate the operational impacts [65]. On a material level, LCA studies on adaptive materials appeared to be mostly missing; available information was found exclusively on materials for thermal energy storage [67–69].

The sources were analysed to identify specific ABT typologies and characters, technological systems, subsystems and materials, potentials and issues highlighted by the experts in the field, and integrated in the mapping by systematizing the information within three areas of focus:

- Parameters affecting the design of ABT characters and features. The aim was to span a broad number of existing concepts, not necessarily related with specific technological solutions;
- Technologies and materials used in ABTs;
- Methods to classify ABTs, to be further used in the mapping structure.

2.2. Parameters

A framework of parameters was developed to support a parametric design approach and allow future integration with upcoming digital tools, as Building Integration Modelling (BIM) and Cyber-Physical Systems (CPS), to enable the use of variables and algorithms to generate alternative concepts.

In addition to the sources identified in the background research (Table A1 Appendix A), the framework integrates a number of additional parameters, borrowed from neighbouring disciplines, in order to allow designers and developers to take into consideration interdisciplinary aspects for the development of ABTs. To identify these parameters, relevant sources were acquired following the top-down approach of the background research. Areas of interest were identified in the fields of sustainable architecture, building and material technologies, biomimetics, parametric architecture, and 3D printing. Parametric architecture, that builds on the concept of feature-controlled composition, was the first logical field of study to integrate having already identified a great number of the factors to control design [58,70]. Parameters from the sustainable architecture field were integrated concerning the design strategies for buildings as a whole (non-specific on facades) [31,33,36] and the technologies of traditional active and passive façade systems [59]. Advancements on innovative building and material technologies [40,71,72] allowed to integrate current innovative material-specific features, but also to open up towards possible future innovation areas. Biomimetic parameters were identified to integrate methods for flexible and adaptive design [28], but also to take into consideration kinetic features [5] and structural responsiveness [58]. Aspects from the field of 3D printing were mainly taken into consideration as a highly probable field of development of façade design for its potential, in terms of function [73], additive manufacturing [74] and integration of flexible features [75]. The type of publications reviewed mostly consisted of comprehensive reviews of the state of the art and terminology in the specific discipline, and in the case of the youngest fields of study, research papers reporting on the latest advancements.

Findings from studies introducing computational methods and optimization techniques were taken into consideration to identify, among all parameters, those with a bigger impact on the overall LCA of a building [63,64,76].

As a result, quantitative and qualitative ABT parameters were distinguished into two interrelated typologies that address different parts within the mapping structure: (i) LCA parameters recurring throughout all life cycle stages; (ii) Design parameters relevant for the functional behaviour, integrated in the LCA Operation stage. Parameters were finally listed, prioritizing those with a greater impact on

the LCA for a building in terms of embodied energy and emissions [62] and field-specific parameters that are effectively controlled by designers and producers [37,64,76].

2.3. Materials and Components

The integration of specific adaptive materials (AMs) is a very important part in the design of ABTs, as these enable the integration of the mutating behaviour in otherwise conventional technologies. An exhaustive list of AMs and AM-integrating components was found in the literature previously identified and sourced from books reporting the use of AM in the fields of architecture and design [40,71,72]. Further detailed information on specific materials was sourced from publications on online databases as ScienceDirect, Scopus and ResearchGate.

Relevant detailed information impacting the sustainability of these system at material- and component-level was integrated in the mapping to provide a more complete information support, which also allowed to identify gaps in the available information and future challenges.

2.4. Mapping Framework

The mapping framework hierarchically organises the afore mentioned parameters, in order to enable a controlled and methodical assessment of all aspects involved in the design of the technology. The mapping is inspired by previous research on LCA strategies in early design stages [37,62,64].

In order to align with the existing tools, the overall outline of the mapping follows the linear process adopted by the LCA approach to product design by the international standards ISO 14040: 2006, ISO 14044:2006 and EN 15804:2012 [39,77,78], and is structured according to the sequenced product life cycle phases [39]. Classifications of ABT categories identified in the background research, whether following a systematic [5,8,51], mixed [10], or biomimetic approach [5], were integrated within this framework to enable eventual shortcuts to available information on substances' emission data, avoiding reconstructing the emissions path of the individual production processes of the materials making up the product. In each stage of the cycle, corresponding LCA parameters are methodically addressed to define all elements of the system and determine the qualitative aspects to include in the assessment as well as the type of quantitative data to input.

The production stage (A1–A3), subdivided into three sub-steps (A1 raw materials supply, A2 transport, A3 manufacturing), covers the cradle to gate processes for materials and services used in the construction. As most adaptive materials are manufactured through a multiple step-process, these sub-steps have been split into (i) pre-products, relating to single raw materials and (ii) product development and manufacturing, where designers potentially have more over the production of elements and components. LCAs in this stage generally refer to material databases (Ecoinvent, Oköbau, etc. [79,80]) as the primary source of information. AMs and AM components (as described in the previous section) being very recently developed are however more difficult to find in these databases. Available LCA relevant information on these materials and components was therefore integrated in this stage. In order to get an overview of available AMs, the paper reports both on AMs that are currently in use in architecture and in other contexts.

In the Construction stage (A4–A5) LCA impacts are considered similar to those of conventional building systems and were therefore not further researched.

Actions and choices in the Use stage (B1–B7) are strongly connected to the specific purpose of the technology. The design of ABTs in this phase is therefore suggested to be controlled by two interdependent processes:

- The definition of the Design parameters (described in the previous Section 2.2). The choice of parameters impacts the operation of the technology and affects all other phases in the life cycle;
- The assessment of operational benefits. In this stage, the mapping aims to enable the integration of results from field-specific assessment tools (i.e., computer simulations of the energy efficiency of specific solutions integrated into building skins) [60,81].

Processes in the End of life stage (C1–C4) and Benefits and loads beyond the product's boundary (D) are considered similar to those of conventional building systems. Considerations therefore mostly focus on the impacts deriving from choices made in the earlier stages.

2.5. Boundaries of the Research

The building system can be described as a specific organised combination of design solutions within the logic of nested systems. The main system (the building technology) encloses subordinate interdependent systems (the building products, materials, etc.,) and is simultaneously enclosed by other superior interdependent systems (the façade, the building, etc.,) [82,83]. This holistic vision at the base of the ecological approach is an important foundation in LCA, which however introduces the need to define boundaries to the system in analysis, in order to enable the assessment in a context where the chain of upstream impacts could potentially be endless [61].

While building products and material products are considered in LCAs as responding to an additive logic, where the impact of a building product is the sum of the impacts of the parts composing it; buildings and adaptive building technologies (ABTs) are synergetic systems based on mutual interaction and transformation, specifically developed for their capacity to synergistically adapt and exchange energy with their environment. The LCA of an ABT can therefore not be reduced to the sum of the impacts of the subordinate parts composing it, but must also take into the evaluation, a broader spectrum of cause-effect chains [66].

Since this mapping aims to support decisions on strategic technology choices, the research's boundaries are identified by the physical boundaries of the technology itself and of those aspects that are relevant to its life cycle, including: the boundaries of its components, the interaction between subsystems, and the secondary impacts on its superior synergetic system (in the architectural context, the building part or the building) as already defined for the energy performance of the building in the 2002/91/EC EU directive [84]. Within this logic, both the downstream flows of embedded resources and impacts, operation and end of life consumption flows, as well as impacts on the upstream operation flows of the superordinate system are considered as inside the system's LCA boundary.

The LCA that the mapping supports is of a prospective type, aiming to look forward at future impacts of the technology [66]. Further time-related boundaries (point in time, or a time period, for which the study is valid) must be further defined by each specific assessment performed within the framework.

The mapping is thought of as a first attempt to organise and list the many inputs that make a successful ABT design process. Although the mapping aims to allow the integration of other tools and systems (BIM, computer modelling tools, Life Cycle Inventories, etc.,) these are considered outside the scope of the present research (Figure 4).

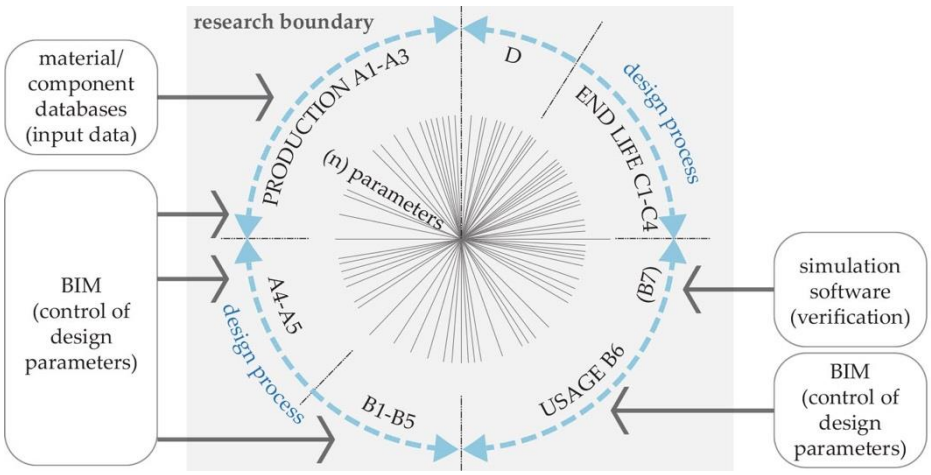

Figure 4. Graphical overview of the use of the mapping, and the boundaries of this research (in grey).

3. Results

The mapping graphically summarized in Figure 5 [60] provides an overview of the complexity of the design parameters involved in the life cycle of ABT.

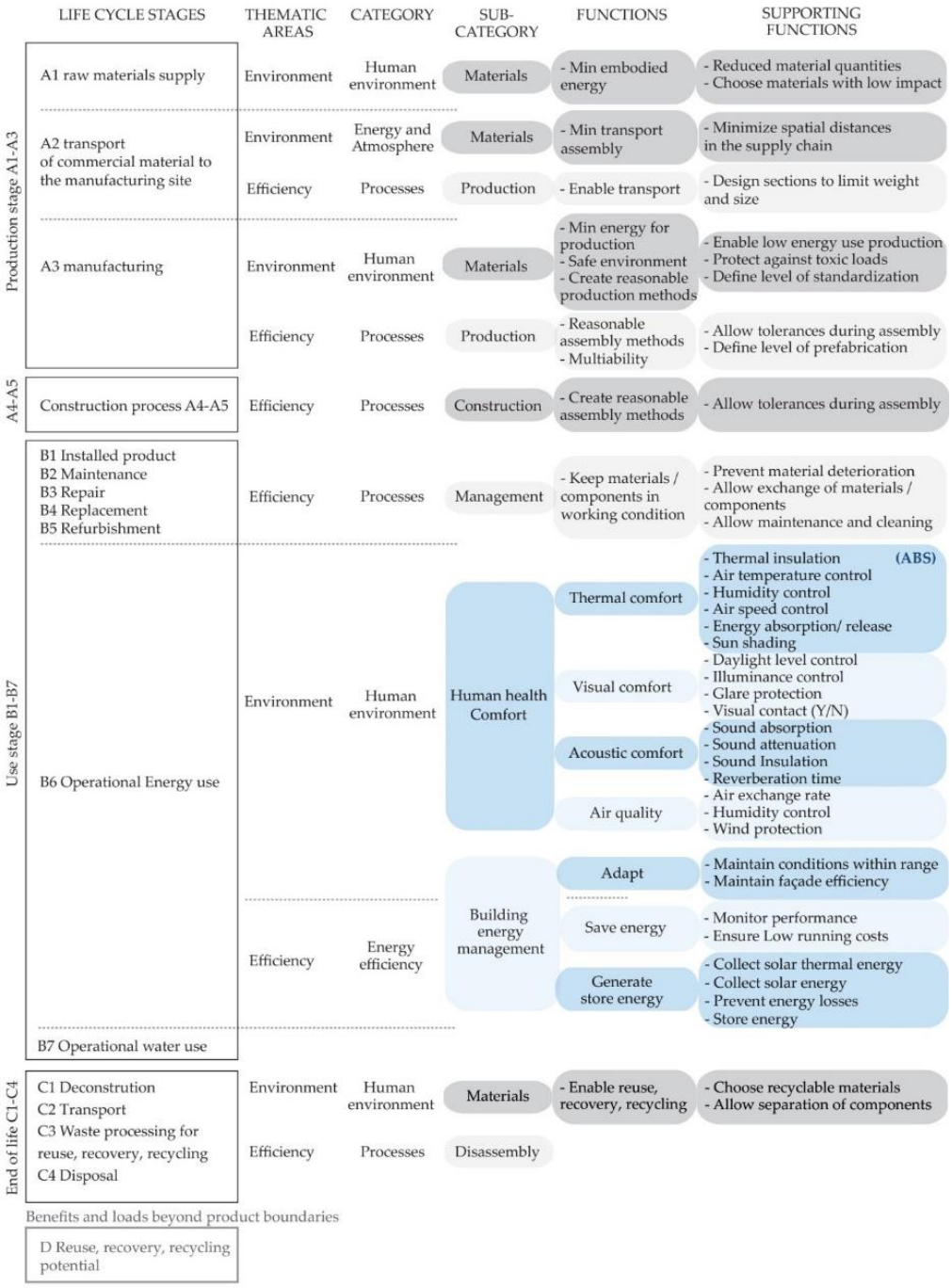

Figure 5. Sustainable categories and functions related to Adaptive Building Technologies (ABT) life cycle (focus on Adaptive Building Skins (ABS) in the usage stage B6).

The list of parameters is not intended to be exhaustive but to be implemented in time, integrating new concepts, and as a way to gather and organize data and information on existing and upcoming materials and technologies. Further LCA-stage specific parameters are presented in Figures 6–10. The next steps of the research will further validate the mapping by assessing selected case studies, identifying potentials for innovation within the projects, and comparing the outcomes.

To identify possible difficulties in building a successful tool and current knowledge gaps, the research has proceeded with analysing, throughout all LCA phases, the differences in method and content that distinguish an Adaptive Building Technology's (ABT) Life Cycle Assessment (LCA) to that of conventional building technologies. Reviewing the state-of-art; the paper has focused on the use of materials, processes and concepts specific to ABTs that are here presented in detail.

3.1. A1–A3 Production Stage

What differentiates adaptive technologies from conventional building technologies is the integration of adaptive materials (AMs) to achieve change. These materials are based on instabilities allowing them to undergo a dynamic change in response to an environmental Energy exchange [72]. AMs can be defined through three parameters characterizing its nature and kinetic behaviour [6]:

- Substance the material is made of (polymers, alloys, wood, ceramic, etc.,);
- Type of effect through which the material reacts (bi-material, shape-memory, shape-change, material absorbing, phase-change effect and electro-active);
- Geometry of the kinesis (linear or volumetric expansion, orientation change through translation/folding/bending or torsion).

3.1.1. A1–A2 Raw Materials and Transport to Manufacturing Site

This section presents a review of the available information on the production of AMs in phases A1–A2, in order to support an early assessment of the sustainability of chosen material solutions in the design phase of the ABTs, while waiting for more detailed assessments to be made available for all pre-products.

As for many new materials on the market, Life Cycle Assessments of AMs still need to be performed and integrated in databases [31,62]. Supplies and manufacturing processes of the raw materials are extremely dependent on factors beyond the boundary conditions (as other technologies, geographical source, stakeholders, market availability, etc.) [17,36]. The LCA parameters involved in the assessment of AMs are listed in Figure 6.

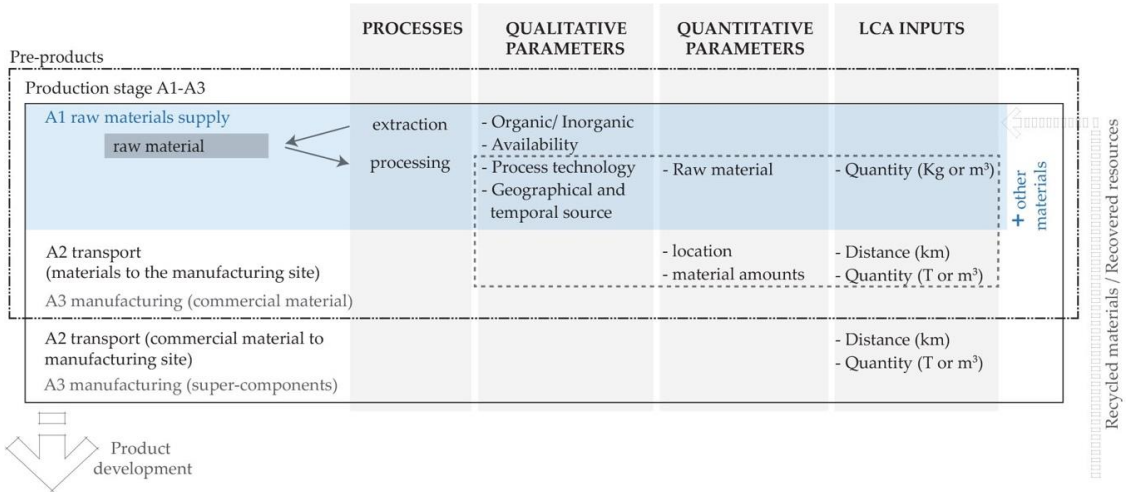

Figure 6. Mapping of LCA parameters for AMs in the phase A1–A2.

At the moment, adaptive materials exist in the form of hydrocarbons and salt hydrates (thermal expansion materials and phase change materials PCM), polymers (shape memory, shape change and bi-materials), metal alloys (bi-metals and shape memory), ceramics (shape-memory) and systems of biological origin (shape memory and PCM) [6]. Further qualitative information on AMs identified from the relative sources is listed below.

Thermal Expansion Materials (TEMs) are materials with an important coefficient of thermal expansion allowing them to undergo considerable changes in volume under specific ranges of temperature change. Table 1 reports on different types of TEMs, production and toxicity.

Table 1. Qualitative information on the production of Thermal Expansion Materials (TEMs).

Type	Name	Production	Toxicity
Organic compounds	Ethyl alcohol (ethanol)	As petrochemical or from natural fermentation [85]	Volatile, flammable, psychoactive [85]
	Glycerine	Plant/animal source through hydrolysis [86]	Non-toxic [86]
	1.3-dioxolane	Used as solvent [87]	Stable, very flammable [87]
	n-alkanes	Refer to PCM	Refer to PCM
	paraffin oils/wax	Refer to PCM	Refer to PCM
Non-organic compounds	Tetrachloroethylene	High temperature chlorinolysis of light hydrocarbons. Produces side products [88]	Group 2A Carcinogen; common soil contaminant difficult to clean up [89].
	Mercury	Can be found in electrical and electronic applications	Extremely toxic and must be securely sealed to avoid spills and inhalation [90]

Energy-exchanging materials include light-, electricity- and hydrogen-storing materials, but are mostly still under development and of difficult availability [40]. Phase Change Materials (PCMs) on the other hand, and specifically thermal PCM (tPCMs) that store and release thermal energy when changing phase from solid to liquid, are employed in buildings as Latent Heat Storage (LHS) units [40,50]. tPCMs are quite extensively researched from an LCA point of view and are generally considered to reduce the energy footprint of buildings although some PCMs have high embodied energy [91]. Table 2 reports on different types of tPCMs, production and toxicity.

Table 2. Qualitative information on the production of thermal PCMs (tPCMs).

Type	Name	Production	Toxicity
Organic compounds	Paraffins (n-alkanes)	Production process similar to other fossil-based materials [69,92,93]. Market presence. Can be made in large quantities, wide range melting points [40,92]. Structurally stable over thousands of melting cycles [92,93]. Non compatible with plastic containers [67,92].	Non corrosive, stable below 500 °C, flammable [67,93]. Leakage hazardous to ground water [40], corrodes building materials [92]. Environmental impact considered similar as other fossil-based materials [69].
	Fatty acids, glycerol	Vegetal or animal derived, or from up-cycled by-products [93], wide range melting points [92] Do not lose their proprieties undergoing the cycles, more expensive than paraffins [67,93]	Mildly corrosive [67,92], some can be toxic at elevated temperatures [61], fully biodegradable [93]. Production impacts water depletion, particulate matter and climate change, but overall environmental impact is lower than paraffins [93].
Inorganic compounds	Salt hydrates	Market presence. Can be made in large quantities [40,92]. Common by-product of industrial/chemical processes [92]. Compatible with plastics, smaller melting point range, wider phase change range; efficiency decreases with each cycle [67].	Corrosive in contact with metal, slightly toxic [92]. Significantly lower contributions to the global warming potential than fossil-based PCMs [68].
	Metallics (low melting point metals/alloys)	High thermal conductivity, used for cooling of electronic equipment, high costs [92].	Might produce corrosion with building material, non-flammable [92]
Eutectics	(mixtures)	n.a.	n.a.

The main LCA issues reported on for the production of tPCMs concerns the type of raw material in use, the number of cycles the tPCM can undergo without losing its proprieties, the need to incapsulate the material, and the compatibility with other materials that make up the packaging [67,94].

Polymers that exhibit environmentally-triggered dynamic proprieties include a very large family of materials, from natural to synthetic origin and are increasingly favoured over alloys for their better shape memory effect, lower density, biodegradability, easier processing, better recovery, programmability and lower cost [95]. Table 3 reporting on different types of AM polymers, production and toxicity therefore focuses on typologies of interest in architecture.

Table 3. Qualitative information on the production of adaptive polymers.

Type	Name	Production	Toxicity
Polymers	Ferroelectric (electroactive effect)	Not available in large quantities [40], activated through voltage	n.a.
	Cross-linked sodium polyacrylate (absorbent effect)	Polymerisation of various components, short replacement life (<10 regeneration cycles), low UV resistance, otherwise maintenance free [40].	n.a.
	Polyethylene terephthalate (PET), Polyethyleneoxid (PEO), etc. (shape memory, shape change) [96]	Processing at lower temperatures in comparison to alloys with the same effects.	Product is not toxic and used for medical applications [72]. Potential biocompatibility and biodegradability;
	Biodegradable polyester (shape memory) [97]		
	Polymers containing cinnamic groups(photo responsive) [98]		
	Polyvinylidenfluoride (PVDF) (piezoelectric)	Mechanical-electric stretching treatment and polarisation under direct electrical current field [40]	Starting compounds are toxic [99] End product is non-toxic [40]
Composite polymers	Acryl-based with graphite coating (electroactive effect)	Films coated on both sides with graphite as electrodes [40]. Not available in large quantities, requires voltage for activation [40].	Repeated layering and winding of the material [59] can make material recovery and recycling difficult.
	Wood flour + thermic polyurethane (TPU/WF)	Mechanical effects can be enhanced by layering with polymers/melt processed [71,99], possible to 3D print [100].	Outdoor exposure can change the visual appearance [72,101]. Layering/mixing can make material recovery and recycling difficult.
Bio-based	Beech/Pine veneer wood (humidity/temperature reactive)	Programming through wetting and loading [102]. Directional shape change [23].	Natural adaptive material, non-toxic, biodegradable, recyclable.
	Natural rubber	Stain-induced crystallization/blending of natural rubber with fatty acids. Possibility to cold-program. Ability to store large strain, tuneable trigger temperature [103].	Applications in biomedical engineering [103], biodegradable

Metals are among the most used raw materials in adaptive technologies due to the versatility in their design on a material level, resistance and broad range of applications [6,40]. AM metals are either bonded as alloys reacting with a thermal/kinetic memory effect (Shape Memory/Change Alloys—SMAs/SCAs) or joined as separate metals that react due to the different thermal expansion coefficient of the two metals (Thermobimetals—TBs) [40,72]. Table 4 reports on different types of AM metals, production and toxicity of specific interest in the architecture context.

Table 4. Qualitative information on the production of AM alloys and metals.

Type	Name	Production	Toxicity
Alloys (SMAs/SCMs) mechanical/thermal activation	Nitinol (NiTi)	Made through casting, vacuum arc melting or induction melting to reduce the impurities [104]. Thermomechanical treatment at high temperature to embed the shape-changing state [40,71,104]. In some cases, several cycles without fatigue [50,72].	Products are mostly not toxic; some are used for medical applications [40,72].
	Copper-zinc-aluminium (CuZnAl)		
	Iron-platinum (FePt)		
	Gold-cadmium (AuCd)		
Alloys (SMAs) magnetic activation	Nickel-Manganese-Gallium (NiMnGa)	Faster reaction and greater movements achievable than in mechanically and thermally activated SMAs [50]	
Composite laminated metals (TBs)	Superinvar (NiCoFe) + Manganese-nickel-copper (MnNiCu)	High-energy, high-temperature production process as metal strips are joined by riveting, brazing or welding [105]. Corrosion-resistant treatment by plating with chrome and copper, layering with copper to improve electrical conductivity [40]. Pre-determined direction of the movement [72].	Non-toxic.
	Superinvar (NiCoFe) + Iron-nickel-manganese-copper (FeNiMnCu)		

Shape Memory Ceramics (SMCs) convert heat into strain and vice versa and can resist high temperatures, although they often incorporate metal alloys [106]. SMCs are researched as a new generation of actuators with high energy output and/or high energy damping [106]. An example are the Zirconia-based ceramics that, although still brittle [106] have shown promising shape memory reversible proprieties [107]. These materials are however still to be further developed and diffused before their use in an architectural context is made possible. No information on their toxicity could be found.

Piezoelectricity is a coupled field effect where stress and strain are coupled to electrical field and polarization, allowing the materials to convert voltage into physical deformation, and vice-versa can also generate electrical charges when deformed mechanically [108]. These proprieties can be found in ceramics (PEC) [40,50], in some organic materials (as in viruses [99], bones [94], spider silk [109] and wood [110]), crystals [40,111], and polymers (see Table 3). Table 5 reports on different types of piezoelectric materials, production and toxicity. These materials are at the moment very little developed in the architectural context.

Table 5. Qualitative information on the production of Shape Memory Ceramics (SMCs).

Type	Name	Production	Toxicity
Inorganic ceramics	Lead zirconate titanate (PZT)	Doping of the ceramics by electrical fields: thermoelectric sintering treatment, and polarisation under electrical current field [40,50]. Charges are proportional to the magnitude of the load [40]	Acute toxicity for man and environment [112]. Release into the atmosphere of lead oxide (PbO). Potassium sodium niobite (KNN) suggested as a PbO-free alternative is however found to have overall greater environmental impacts than PZT [113]
	Lead magnesium niobite (PMN)	n.a.	
Organic materials	Dry bone [108]	Found in nature	Stable, biocompatible, biodegradable
	Silk [109]		
	Wood [110]		
	M13 bacteriophage	Piezo response force microscopy-Phage gene modification [99]	
Monocrystals	Quartz crystals	Found in nature Of secondary importance in modern technology [40]	Stable, biocompatible
	Tourmaline crystals		
	Sodium potassium tartrate	Reaction of potassium acid tartare, water and sodium carbonate [111]	Not toxic, used as food additive [111]

3.1.2. A3 Manufacturing

This section presents a review of the available AM components and their relative manufacturing processes in stage A3, in order to support an early assessment of the sustainability of chosen solutions in the design phase of the components, while waiting for more detailed assessments and EPDs to be made available for these products.

During the development of pre-products, most AM materials are further combined to integrate additional proprieties, before being shaped into their final commercial form (plates, strips, sheets, cylinders, etc.,). During the product development stage, commercial materials are combined, depending on their future use, with an additive logic to create systems with growing complexity, from elements to sub-components and to components. The LCA parameters involved in the assessment of AM components are listed in Figure 7.

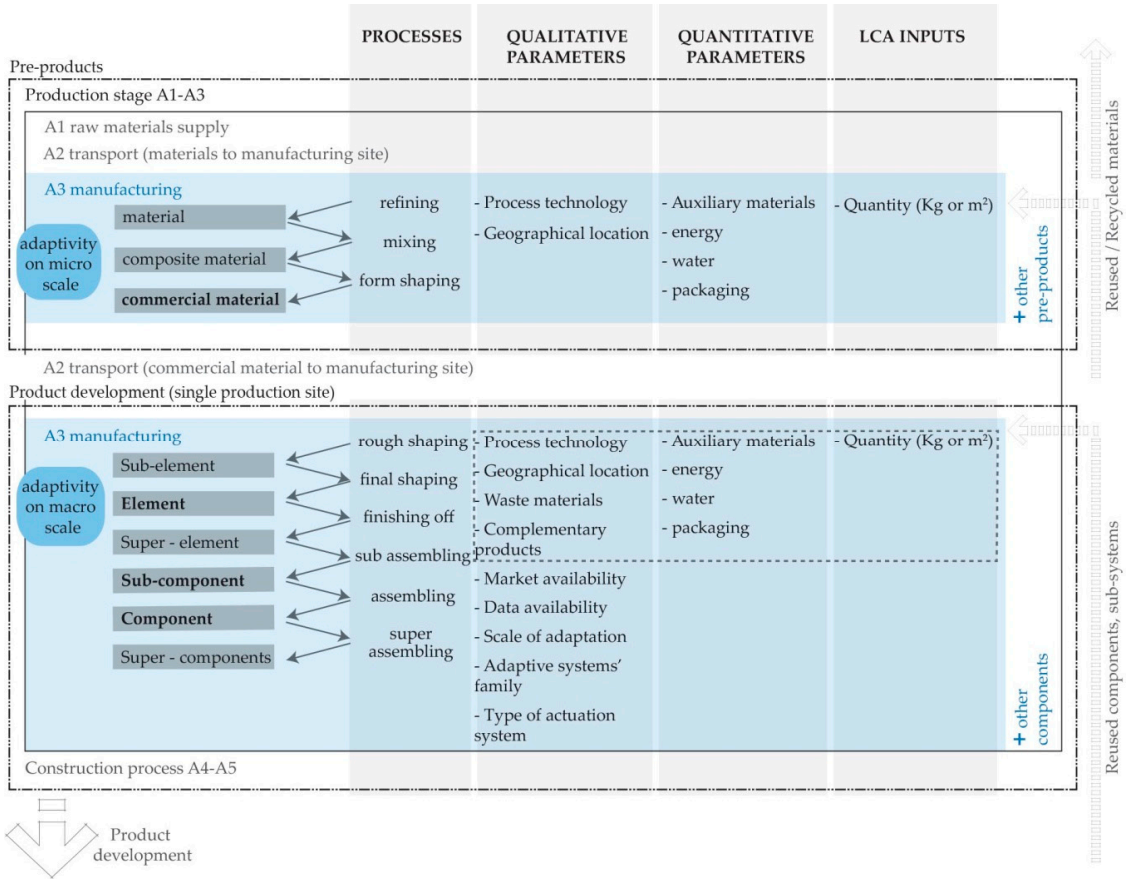

Figure 7. Mapping of LCA parameters for AM-components in the phase A3.

TEMs are integrated into a broad range of building products, from thermostats, sprinkler systems, operating valves, as well as in facades and room ventilation systems [40] and not least pre-assembled products as thermocylinders (heat-activated pistons) that have further integration potential in architectural elements [57]. No information was found on the manufacturing costs of these components. Table 6 reports on different variations of thermocylinders and the LCA aspects involved.

Table 6. Qualitative Life Cycle Assessments (LCA) considerations on TEM thermocylinder components.

Material	Commercial Material	Element/Component	LCA considerations
TEM	Cylindric pistons (linear motion)	Integration in facades/greenhouses [40]	Design of the pistons on one hand prevents TEM leakage, on the other hand makes separation and recovery of materials difficult (phases C3 and C4)
	Circular pistons (rotational motion)		

Potential benefits from the application of tPCM as LHS units in buildings vary consistently with the geographical location and the thickness of the PCM elements [92,93]. Further questions regarding the sustainability of tPCMs are raised following the need to encapsulate the materials, and more

specifically regarding eventual leakage issues and recycling issues in the end of life phase [48,52,53,67,94]. Parameters that are not known concerning the use of paraffins in architecture concern their efficiency and operation over long timeframes [40]. Until now the PCM lifespan is expected to be of 25 years without losses [71]. Table 7 reports in more detail on the available tPCM-integrating components and the LCA aspects involved.

Table 7. Qualitative LCA considerations on tPCM components.

Material	Commercial Material	Element/Component	LCA Considerations
Organic Inorganic Eutectics	Melted PCM	Immersion of the building material into the PCM, (capillary absorption) [91].	In case of capillary absorption separation of PCM and other materials is not possible (phases C3 and C4).
	Micro-encapsulated (µe-PCM)	Construction materials (concrete with low-energy storage capacity) [53,92,93]	µe-insertion solves leakage issues (but at high temperatures, concerns for fire-security/structural stability), limits concrete strength [92]. Separation/recovery of materials difficult (phases C3 C4)
	Powder form	Incorporated with plaster/chipboard/fillers [40,53,91]	Separation and recovery of useful materials is difficult (phases C3 and C4)
	Plastic-encapsulated (rigid packaging/pouches)	For integration in ceiling/walls [40,71,91]. PCM insulated glazing units [71].	Packaging makes the replacement and disassembly possible (phases B4 and C3). Leaks can be hazardous to health and cause damage to other components [40,92].
	Aluminium foil bags		

Polymeric AMs are often combined through repeated layering in their construction to enhance the adaptive proprieties of the materials before being sold as commercial materials [40,71,72]. If on one hand the material combinations enable to embed a great variety of adaptive effects as shape memory (SMP), shape change (SCP), absorbent (Aps)/superabsorbent (SAP), electroactive (EAP), on the other hand, it raises issues regarding material separation in the end of life stage. At the same time, biodegradable solutions are increasingly developed, possibly becoming a solution to the waste processing issue [97]. Table 8 reports on the available components and the LCA aspects involved.

Table 8. Qualitative LCA considerations on adaptive polymer components.

Material	Commercial Material	Element/Component	LCA Considerations
Polymers/Composite polymers	Powders compressed in a plastic profile	Hydrogel band as absorbents/sealers [40]	Encapsulation makes the replacement and disassembly possible (phases B4 and C3);
	Granulates	Bag fillings, water absorbent, interlayered between textiles [40]	
	Fibres, yarns	Woven into textiles, sometimes with additional protective coating [40], biomedical instruments [95]	Coatings can make recovery of useful materials difficult (phases C3 and C4)
	Strips, films often multi-layered or winded to enhance the performance	Casing components Conductive piezo-deforming coatings on micro and macro level, sensors [40], actuators [95]	Multi-layering can make recovery of useful materials difficult (phases C3 and C4)
	Coils	Spring elements, actuating and positioning drives for robots	n.a.

Metallic AM components are available in a great number of shapes and products and are increasingly in use in architecture [49,114]. Table 9 reports on the available components and the LCA aspects involved.

Table 9. Qualitative LCA considerations on adaptive metal/alloy integrating components.

Material	Commercial Material	Element/Component	LCA Considerations
SMAs/SCAs	Wires, rods full-section or hollow	Textiles, connection/control/actuating elements [71,72]	Separation and recovery of useful materials can become difficult (phases C3 and C4)
	Springs	Spring elements, connection/control/actuating elements [40]	
	Bands, strips	Hook/loop fasteners, control/connection/actuating elements	
	Sheets	Construction membranes [40]	
	Clamps, stents/special shapes	connection/control/regulating actuating/positioning elements [40].	
TBs	Strips/U-profile/ curved/combined	Actuators or positioner drives, thermal control and regulating elements [105], springs, compensating elements [40,72]	Flexible design potential. Often manufactured for specific applications [40,72,105]. Long replacement life if not overloaded [40]; Multi-process step (depending on alloy, shape, assembly) raises LCA impacts.
	Reverse strips		
	Spirals, helices		
	Discs		

Piezoelectric materials are mostly used as vibrating elements in clocks, speakers, microphones, sensors and actuators [108], and only marginally for their electricity-generating capacity due to the lower efficiency in comparison to other sources of clean energy [40]. Some developments have however surfaced in the field of architecture, integrated in energy-generating floorings [49] and theorised as energy-generating facades integrating P(VDF-TrFE) Piezoelectric films with electrodes [115]. No application has been found for organic piezo-materials. For Piezo-polymers refer to Table 8. Table 10 sums up the available components identified and the LCA aspects involved in PECs.

Table 10. Qualitative LCA considerations on piezo-materials.

Material	Commercial Material	Element/Component	LCA Considerations
PEC	Fibres, plates [50]	Generators, energy-independent sensors, micro-positioning and vibration absorbers [40]	Multilayering makes separation and recovery of useful materials is difficult (phases C3 and C4)
	Monolithic bender actuators		
	Monolithic linear actuators		
	Friction dampers [50]		
M13 Bacteriophage	Thin films [99]	Piezoelectric generator [99]	Still needs to be developed, not market available. Potentially environmentally friendly piezoelectric energy generation [99]

3.2. *A4–A5 Construction Process*

The construction process A4-A5 covers the unit processes from the factory gate of the building system's super-components to the completion of the construction work on site (transport and installation). Impacts in this phase are considered similar to those of other conventional building systems and are therefore not further researched. For completeness of the mapping structure, the corresponding qualitative and quantitative parameters have been listed in Figure 8.

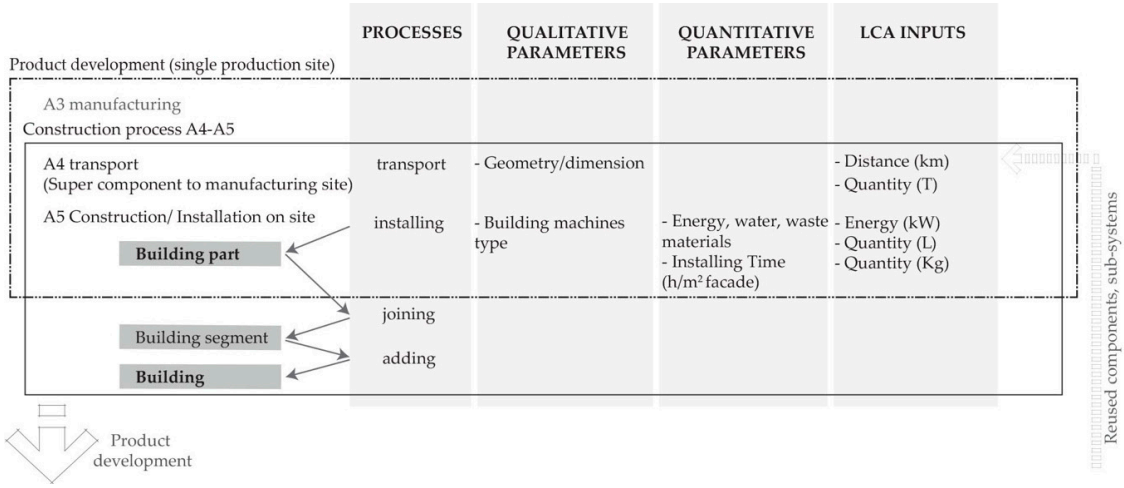

Figure 8. Mapping of LCA parameters in the phase A4–A5.

3.3. B1–B7 Use Stage

This section, the main qualitative and quantitative parameters to consider in the usage stage of an ABT have been reviewed, in order to support an early assessment of the sustainability of chosen solutions in the design phase of the components.

In the use stage, phases B1–B5 pertain to actions during the usage life of the product, while phase B6 Operational energy use (Figure 9), is probably the most challenging and significative stage of an ABT's life because of its characteristics and functions. As the evaluation parameters in stage B6 strongly vary with the nature and the specific goals of the superordinate system the ABTs are integrated in, parameters applying to a specific case study, Adaptive Building Skins (ABSs), have been inserted as an example.

Stages B1–B5 strongly depend on the accessibility of the dynamic components. AMs are generally considered to be relatively low-maintenance (B2) as long as the components are not loaded over their limits and are protected from particularly harsh conditions, as outdoor conditions (wind, rain, direct sun, dust, etc.,) in the case of ABS [40]. Hence, ABTs are at the moment mostly installed in sheltered or indoor areas [10], or with specific protective screens [10,56].

Replacement (B4) and Refurbishment (B5) are enabled through disassembly. ABTs often have the advantage of being manufactured with an additive logic in order to allow the integration of the commercial materials, the elements or the components in existing structures or products. In the best case, it is possible to separate components down to the material level, but in some cases materials and parts are irreversibly linked to one another and complicated to separate. The potential to replace the AMs within a component made of conventional functional parts, is extremely important in ABTs as it enables not only the substitution of AMs with a shorter lifetime (see also Section 3.4 End of life), but most of all it enables a resource-efficient technological upgrading as new and more efficient, more sustainable AM solutions are being discovered.

It is however for the potential energy-savings in phase B6 Operational energy use that ABTs are mainly developed. As stated in the mapping boundaries (Section 2.5), the physical boundaries of the technology and of the aspects relevant to its life cycle include, together with the downstream flows of embedded resources and impacts discussed in phases A1–A5, also the secondary impacts of the building technology on the operation consumption flows of its superordinate system. As each type of ABT is tailored on the specific goals to achieve in phase B6, Adaptive Building Skins (ABSs) are presented as an example, as a superordinate system to the ABT.

ABSs are a specific family of multifunctional facade systems able to change their features or behaviour over time in response to transient performance requirements and boundary conditions to improve the building performance in terms of energy and comfort [8,11]. Indoor Environmental

Quality (IEQ) and Energy Management are achieved through the regulation of the building skin which integrates a broad variety of different building systems (as highlighted in Table A2, Appendix A), from Building Integrated Solar Thermal [46] to Autoreactive systems [5,55,56]. Some ABSs integrate ABTs with the aim to achieve enhanced reactivity and reduced building energy demands (intended as those defined by the 2002/91/EC EU directive [84]).

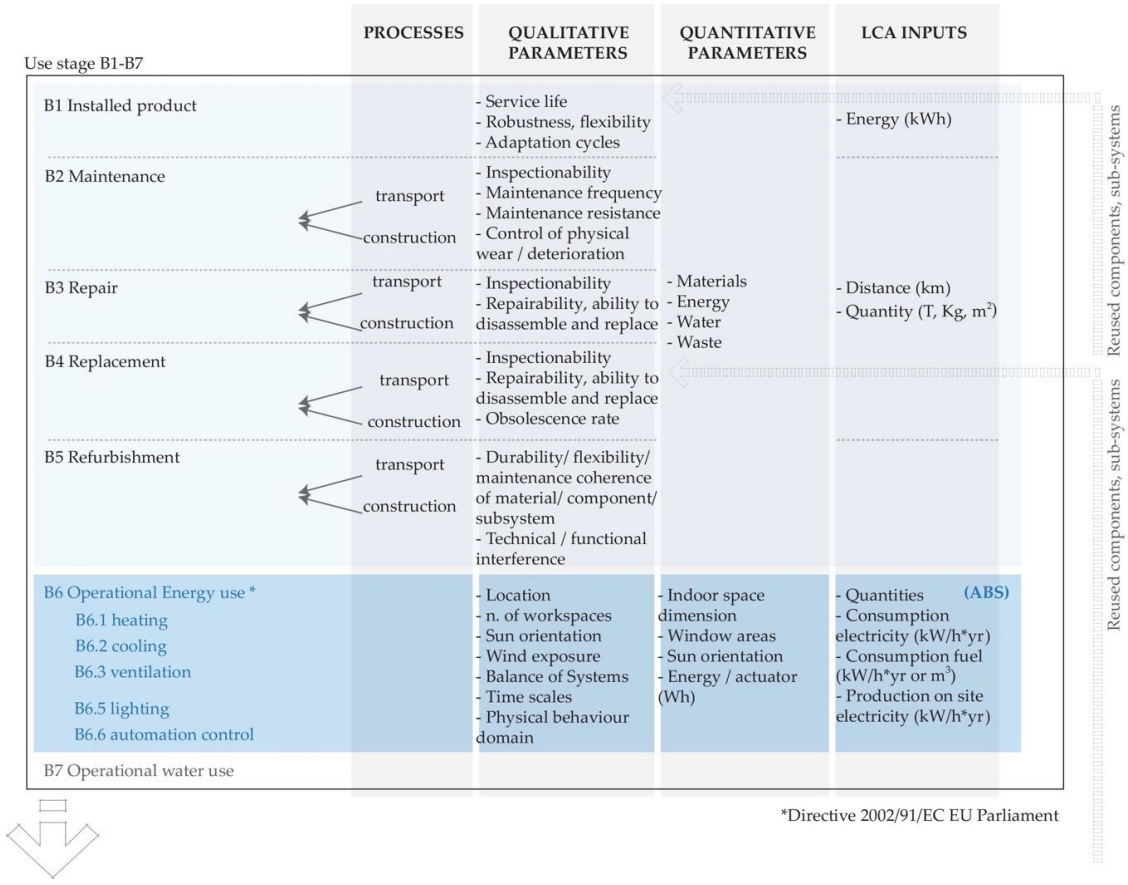

Figure 9. Mapping of LCA parameters in the phase B1-B7, focus on ABS parameters in phase B6-B7.

The impacts of the integration of an ABT in and ABS are of two types and can be assessed with respect to the conventional building systems they are meant to replace.

- A quantitative optimization of the OE of the façade system, where the benefits are straightforward and can be numerically calculated in terms of reduced energy consumption, as in the case of an ABT upgrading an active (powered) ABSs;
- A qualitative optimization of the ABS, that must be assessed on the building as a whole through the use of dynamic energy simulation tools, as when upgrading an active or a passive (unpowered) building technology to optimize its performance. In this case, the benefits are both numerically quantifiable in terms of reduced energy consumption, although the calculations are less straightforward, and qualitatively in terms of user satisfaction and technological simplification.

ABS design parameters either describe the functional behavior of the façade system (goal, responsive function, operation, technologies, responsive time, spatial scale, visibility, degree of adaptability) [8,51]; or physical features (active/passive behavior, opaque/semi-transparent/transparent/translucent appearance) [59]. Other parameters of great importance for the LCA relate to the robustness and flexibility of the system (adaptability, multi-ability and evolvability) [20], which are not exclusively important to ABTs, but to all products.

The service life of innovative technological components as ABTs can only be estimated, as reliable data is not yet available, but can safely be considered to be shorter than that of traditional building elements (i.e., 20 years) [114].

ABS do not generally involve any Operational water use in phase (B7), but ABTs can theoretically be used to regulate the water use within other building systems. In this case, the same considerations as in phase B6 apply to the technology.

3.4. C1–C4 End of Life

The End of life stage C1–C4 covers the de-construction of the building or its parts, that includes on-site operations, transport to disposal and all re-use or recycling processes if any. The LCA parameters involved in the assessment of AM components are listed in Figure 10.

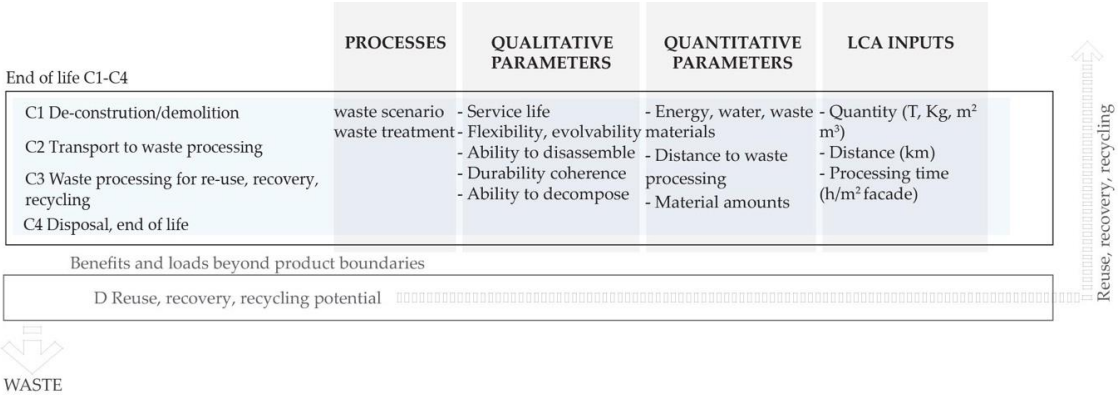

Figure 10. Mapping of LCA parameters in the phase C1–C4.

As for any other conventional building component, the successful recovery of all possible kinds of resources depend on two main factors: (i) the disassembly potential of the component to obtain clean, single material parts; (ii) material reusability and recyclability potential.

Disassembly in AM-integrating components (as discussed in Section 3.3 Use stage) can facilitate and speed-up deconstruction (C1) and have positive impacts on eventual Transport (C2) by reducing the size and the weight of the materials to displace. In the waste processing phase (C3), focus is set on AMs, as all other parts composing the ABT can be assessed and processed as conventional building parts.

Re-use of AM materials and parts depends on the usage life of the material, or how many change cycles it can achieve before exhausting the adaptive capacity or showing signs of wear. These materials being very new, their usage life is for most of them not proved through experience, but in the best case hypothesized through lab-testing [68,69,93].

In those cases where the AMs can be effectively separated from the other materials or building components, recyclability of AMs seems for the moment still difficult [17,40,93]. Many AMs are difficult to recycle (non-organic TEMs [40,90]) or recycling is hindered by the inability to separate the materials within the composed materials (composite polymers, alloys, μe-PCM [92]). Non-toxic or bio-compatible materials (glycerine based TEM and tPCMs, PET polymers, bio-based polymers [102,103]) are strongly growing in number and are starting to become market available.

4. Discussion

As the literature review and the results section have highlighted, a great amount of information at the base of a Life Cycle Assessment for ABTs is already available within the state of knowledge of the specific disciplines. This paper has therefore reviewed relevant aspects in different disciplines in order to map a framework on which to further develop an ABT LCA.

In general terms, what is at the moment missing in order to proceed with the effective enabling of ABTs LCA are the quantitative data inputs from not yet performed, not publicly available, not complete, or not comparable data from Environmental Product Declarations (EPD) or LCAs. On the other hand, although being a very new building technology, ABTs are starting to become sufficiently theorised and developed so as to enable to outline an LCA mapping structure based on the foreseen development directions and design opportunities.

As the framework illustrates, the main differences between the LCA of ABTs and that of conventional building systems can be found in the production and manufacturing stage (A1–A3) and the usage stage (B1–B7), with important consequences in the end of life stage (C1–C4). As the literature review has shown, the parameters presently controlled by designers concerns exclusively the usage phase. The mapping highlights for each LCA stage additional parameters and design strategies to broaden the range of active involvement of the designers to the complete life cycle of the technology.

4.1. A1–A3 Production Stage

The use of AMs in ABTs involves the integration of unprecedented features in a known system, which is typical of any highly innovative technology, and is at the same time both its main potential and drawback. As the new technology promises unprecedented benefits for its users, the drawbacks can be difficult to predict, and are in many cases properly assessed only after years of use.

4.1.1. A1–A2 Raw Materials and Transport to Manufacturing Site

The extraction and use of rare raw materials, that are in some cases absolutely necessary to specific components in ABTs, is one of the major arguments that could discourage the development of these technologies. While it is true that many of these materials integrate toxic or rare raw materials and undergo high-resource requiring and polluting processing phases; it is also true that, due to their high cost, these materials are often integrated in limited quantities in the parts where reaction is controlled within the building component [5,6,57]. What remains to be seen is if the use of ABTs will increase in the future as in this case, the quantity produced of these materials is also bound to increase. If so, the contribution of these ABTs in terms of embodied environmental impacts need to be balanced out by energy and resource savings in other LCA stages (as during operation) to be still considered of interest. Studies effectively comparing the operational benefits of the technology against the drawbacks of the resource-consuming material production appear to be still missing.

Bio-compatible and eco-friendly AM solutions are however already available as the field of material sciences is quickly developing clean alternatives with increasingly better adaptive performance, either using less resource consuming productive processes [40,71,72], or biodegradable alternatives [95,97]. Bio-AMs can therefore be expected to quickly improve their service life and become increasingly cheap and interesting for the field of architecture. Big progress is also expected from the field of synthetic biology (synbio), developing previously unimaginable adaptive proprieties, bio-compatible materials and production processes [116]. In the case of more experimental solutions, time is still necessary to allow these to develop enough to become market available and relatively inexpensive to enable their use in an architectural context.

For most AMs described, LCAs and Environmental Product Declarations (EPD) still need to be performed and integrated in the databases. This is however a complicated process, that might take time as the supplies and manufacturing processes of raw materials are extremely dependent on factors beyond the boundary conditions (as other technologies, geographical source, stakeholders, market availability, etc.,) [36,62]. In components these issues add up as energy inputs, production and material LCA costs of all additional parts employed and need to be considered. Moreover, complete assessments will be available only in many years, as aspects as the exhaustion of the phase change proprieties, wear and damage, that have strong impacts on the life span of the product become known. PCMs for instance, that are among the oldest AMs in use in architecture [40], have rarely been in operation for more than ten years [94].

In general terms, existing databases need to be integrated and harmonized between countries so as to become truly operative. Experts and research communities need to solve issues related to inconsistency, transparency, comparability, availability and quality of the collected data [33]. Among the tools that are expected to improve the acquisition of necessary building data in the early design stages, Building Information Modelling (BIM) is considered as an effective platform, which would also allow to codify specific design parameters of an LCA context [76,117]. More specifically, EPD data could be integrated into BIM design files to reduce time-consumption and improve data quality in the early design phase [33].

Designers' contributions in this stage are essentially restricted to the choice between material solutions made available by producers, which however still remains a decision with an extremely high potential LCA impact [32]. Waiting for more integrated tools to be made available, this paper has collected important qualitative information on the production of AMs and AM components for designers to take into consideration. This is one first step towards a first assessment in the conceptual design-phase of ABTs, waiting for full AM LCA assessments to be available. This work will be further deepened in a second phase of future research which will address the availability of life-cycle inventory data for AMs, and the estimation of the cradle-to-gate impacts of these technologies.

4.1.2. A3 Manufacturing

ABTs are mostly integrated in one single component or super-component and are manufactured through a multiple step-process. The stage of product development and manufacturing is in general the one with more innovation potential for architects and designers, which is reflected by the presence of a broad variation in design choices offered by the industries (as in the case of SMAs) [40,71,72], and by the fact that many composite materials and elements are manufactured upon request and for specific use (AM alloys) [40].

From an LCA point of view, focused actions that need to be further taken into account to make ABTs more sustainable in the manufacturing phase include:

- Designing all components for disassembly;
- Planning for possible reuse of the AMs, especially in the case of composite AMs and other materials difficult to recycle;
- Encourage the research and diffusion of new and less resource-using manufacturing processes;
- Optimize the quantitative use of materials in the components;
- Identify and map the products, appropriate units of measure and quantities necessary to build the ABTs that are mainly in use;
- Integrate LCA databases, Life Cycle Inventories (LCI) and Environmental Product Declarations (EPDs) with available accurate information so as not to under evaluate any potential impacts;
- Implementation and comparison of the terminology and ontology of ABT products with BIM libraries and standards to facilitate the LCA process and to allow a shared base of understanding from design to facility management [76,117].

4.2. A4–A5 Construction Process

The LCA impacts in the construction process expected from the integration of ABTs within the building system are expected to be the same as those of conventional building components and are therefore purposely not further deepened.

The development of new materials is however opening up to innovative on-site and numerical construction processes [73–75] which seem very promising for the future of architecture, cutting a great amount of resources that are traditionally needed—in terms of material, transport, and not least professional expertise [118]. Any combinations with the field of ABTs are for the moment unexplored. However, as these two fields develop parallelly, it remains to be seen how a meeting between the two technologies in the near future can impact the ABTs LCA.

4.3. B1–B7 Use Stage

The savings in operational energy use are supposedly the main asset of ABTs, especially in the case of autoreactive technologies. The benefits of integrating ABTs have so far mostly been theorized—in terms of kinetics and operation [5], technology, use and systematization of categories [8,10,51]—anticipating the full consumption assessments to achieve proof of concept [9] on the base of dynamic energy simulations and LCA studies quantifying the energy effectively required for building automation with respect to ABTs.

ABTs can be expected to have similar drawbacks as AMs, and more specifically short and fragmented service life in the stages B1–B5 due to a speeding up demand for technological upgrading and to the availability of increasingly more efficient solutions. Hence, whether integrating powered or autoreactive AMs, ABTs need to be designed so that each material, component and subsystem is integrated coherently with its service life, probability of becoming obsolete and future market availability, while easing inspection, reparation and most of all replacement.

In the operating phase B6, the effective capacity of ABTs to reduce the energy demand in buildings and optimize the environmental comfort conditions needs to be demonstrated by the research community in order to enable a complete LCA.

As LCA research has moved towards extensive case-to-case methodological studies in the absence of common guidelines, assessments typically differ in matter of scope, methodology used, of functional units and system boundaries with the disadvantage of achieving limited possibilities of comparison and benchmarking the results [31,62].

4.4. C1–C4 End of Life

Functional life duration of AMs set apart, ABTs can be expected to have a short usage life in comparison with their production costs due to the fastening rate of technological upgrading. Evolvability and re-usability are therefore the most significant parameters for these systems in the End of life stage C1-C4, together with disassembly and re-use potential. Waste can be seen more as a lack of purpose rather than the inherent value of a specific element [119], and in adaptive as well as in more traditional systems no further advancements in knowledge are needed to enable new design scenarios. This is therefore an action area of immediate priority for designers and architects.

What is of no lesser importance, and which goes hand in hand with embedding disassembly, is to rethink the products so as to effectively enable that the lengthened usage life of the products is put into practice. Although some products are designed for disassembly, many are still treated as regular waste, not only not being partially reused, but also not being taken apart for material recycling. While the systematic organisation of the recovery and recycling processes fall on local administrative bodies, what is of importance in the end of life phase for the next generation of thinkers, is to socially diffuse and promote disassembly and reuse products by conceptualizing attractive new and smart functions that engages the potential users.

5. Conclusions

The building context is one of the fields with greater potential to impact everyday human life and, not least, the environment. Therefore, architecture cannot afford to innovate passively, awaiting applications to be transferred from other fields of study. Adaptive Building Technologies (ABTs) have opened up a growing field of research in Architecture aimed at improving the overall building performance, ensuring comfort while reducing operational energy consumption. Although being mostly at an experimental stage and still under development, ABTs are considered of strategic importance in terms of simplification and design optimization of conventional building technologies, reducing planning imperfections, operating difficulties as well as maintenance costs, becoming exponentially reliable. These new technologies are however rarely designed within the broader frame of sustainability over their entire lifecycle. How sustainable these zero energy technologies really are is

yet to be established. As Design can change the way we conceive our usage and production schemes, as well as raise public awareness, the new generation of thinkers needs to be increasingly involved in the logics of LCA and introduced in the early stages of our production processes.

This paper is one first step in the process of building a flexible easy-to-use LCA tool to support creative innovation and design of ABTs. The work sets the base in terms of structure and contents for the building of the tool though:

- Reviewing the existing state-of-art on ABTs and its future developments through qualitative top-down approach and a holistic document analysis (Appendix A). As ABTs is a new and fast developing interdisciplinary field of study, information has been sourced from a number of interconnected disciplines—as sustainable architecture, building and materials technology, biomimetics, parametric architecture, 3D printing, and digital tools as Building Integration Modelling (BIM) and Cyber-Physical Systems (CPS). The research was conducted through online available databases as ScienceDirect, Scopus, ResearchGate, and through the university libraries of the authors' home universities;
- Identifying relevant parameters defining the design of ABTs in all LCA stages (Figures 6–10);
- Graphically and hierarchical organizing the elements of the system as a map of parameters (Figure 5) to enable the final LCA tool to support a parametric design approach and enable the use of variables and algorithms to generate alternative design concepts;
- Identifying specific materials, processes, concepts and parameters specific to the design of ABTs (as compared to conventional building technologies) in order to highlight difficulties and knowledge gaps and enable the successive research phases to build on the existing State-of-Art;
- Assessing the potential for ABT design optimization in each LCA stage.

Specific findings highlighted in the paper are: (i) ABTs are identified on material scale by the integration of Adaptive Materials (AMs). Many AMs were found to originate from unsustainable, resource-consuming and toxic extraction and production processes. A number of environmentally friendly alternatives are however available and many more are expected to be rapidly developed. On material level, Designers' contributions are essentially restricted to the choice between solutions made available by producers, reducing the use of toxic and resource-consuming AMs by using them sparingly or not at all. (ii) Manufacturing of ABTs is typically achieved through the assembly of partially customizable parts. In this phase, designers can substantially impact the design of products through smart design and design for disassembly, prolonging the usage life of the technology and its parts. (iii) In the operating phase, the effective capacity of ABTs to reduce the energy demand in buildings and optimize the environmental comfort conditions needs to be demonstrated by the research community in order to enable a complete LCA. (iv) In the end of life stage, the success or failure of the choices made in the design and production phase are revealed. The main actions for architects and designers to improve on the LCA of ABTs involves enabling the actual performance of the disassembly through the development of new concepts to maximize and diffuse the reuse of AMs and other component parts.

In this paper a broad and complex field of study, has been addressed: Adaptive Building Technologies are currently under development and can therefore be expected to evolve in many unexpected ways. The research and the review are therefore not intended to be exhaustive, but to stand as a base and support for further research and development, in science as well as in design. The mapping is thought of as a flexible structure—to gather and organize data and information—to be implemented and integrated, changing its morphology over time as the technology evolves.

To pursue the building of an ABT LCA tool, the next phases of research aim to collect and integrate the mapping with ABT relevant data from Life Cycle Inventories and energy simulations in order to build up a new database for ABTs. The tool aims to be further validated by assessing selected case studies, identifying potentials for innovation within the projects, and comparing the outcomes.

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Appendix A

Table A1. Literature review on ABTs, relative materials and components: contents review.

Ref.	Topic	Focus/SAS [1]	Materials/Components Terminology
[4]	Interactive architecture	Technology development e/g/i/l	Interactive technology, reactive systems, kinetic systems
[5]	Autoreactive architectural facades	Energy, movement j/t/u	Unpowered kinetic building skins; Adaptive systems: responsive, reactive, interactive, autoreactive; Motion parameters: System type, geometry, energy
[6]	Adaptive materials, Autoreactive Building Skins (ABS)	Materials State-of-Art g/n/t/u	Type of energy in the environment: radiant, potential, kinetic; Adaptivity in materials: SMP, SCP, TEM, TB, TBM, SCP, SMP, SMA, SMF, SMC, SM-BS, BM, Aps, SAPs
[8]	Climate Adaptive Building Shells (CABS)	Technology State-of-Art e/h/j/k/l/m/n/t	Relevant physics; Time scale; Scale of adaptation; Control type; Typology
[10]	Climate Adaptive Building Shells (CABS)	Technology State-of-Art e/h/j/k/l/m/n/t	PV; Advanced materials; Facade glazing; Facade shading; Control systems; Facade functions
[11]	Dynamic Adaptive Building Envelopes (DABE)	Technology State-of-Art e/h/j/k/l/m/n/t	Methods of actuation: motor based, hydraulic actuators, pneumatic actuators, material based; Robotic materials; Smart glass
[12]	Shape-memory polymers in CABS	Material J/k/n/t/u	Shape-memory polymers; Climate adaptive building façades; Dynamic materials; Smart materials; smart tiles
[13]	Adaptive thin glass facade panels	Technology j/k/m/n/t	Chemically strengthened Thin glass; Adaptive panels; Lightweight façade; Kinetic façade
[28]	Environmental adaptation in building envelope design	Biomimicry, Design j/k/l/t	Environmental adaptation; Adaptation means;
[40]	Smart materials	Materials State-of-Art n/t/u	PCM, SM/SCM, AM polymers, Thermobimetals, AM alloys, piezoelectric materials
[41]	Acclimated Kinetic building Envelopes (AKE)	Technology State-of-Art, Energy h/j/k/n/t/u	Acclimated Kinetic building Envelope (AKE); Static vs Kinetic; (climate) responsive, active, intelligent, (climatic) adaptive, smart, interactive, (high) performative, kinetic, dynamic; Architectural aesthetics; Solar responsive, air-flow responsive;
[42]	Kinetic building skins	Movement e/h/l	Responsive facades: Reactive facades; Interactive facades
[43]	Sensing, actuation, computation, communication materials	Materials k/n/t	Sensing; Actuation; Multifunctional materials; Robotic materials; Shape-changing materials
[44]	High performance facades	Daylighting, Energy j/k/m/t/u	IOT-based sensor network: dynamic facade, sensor, controllable lighting, user input
[45]	Solar cool facades	Technology State-of-Art, Energy j/m/n/t/u	Solar cooling technologies; integration; high-performance, intelligent, adaptive facades
[46]	Opaque solar facades	Technology State-of-Art h/j/k/m/n/t/u	Building-integrated solar thermal system (BIST); Building-integrated photovoltaic system (BIPV); Building-integrated photovoltaic thermal system (BIPV/T); Thermal storage wall; Solar chimney

Table A1. *Cont.*

Ref.	Topic	Focus/SAS [1]	Materials/Components Terminology
[47]	Transparent and translucent solar facades	Technology State-of-Art h/j/k/m/n/t/u	Mechanically ventilated facade (MVF); Semi-transparent building-integrated photovoltaic system (STBIPV); Semi-transparent building-integrated photovoltaic thermal system (STBIPV/T); Naturally ventilated transparent facade (NVTF)
[48]	Double-skin BiPV façade ventilation, PCM	Technology, material j/k/n/t/u	PCM ; double-skin BiPV façades
[49]	Piezoelectric flooring	Technology, energy t/u	Piezoelectricity, energy-harvesting building technology
[50]	Adaptive technologies and materials	Materials State-of-Art k/n/t/u	Application areas for smart materials: piezo-materials, SCM/SMM, PCM, bio-based composites
[51]	Adaptive facades	Technology State-of-Art e/h/j/l/m/n/t/u	Unified and systematic characterization; Facade classification; Responsive function; Operation: intrinsic, extrinsic; Response time; Spatial scale; Visibility; Adaptability; Dynamic exterior shading and louver facades; PCM glazing; BIPV double-skin
[52]	PCM Window Panel	Technology, material j/k/n/t/u	PCM
[53]	PCM-enhanced mortar, building component	Technology, material j/k/n/t/u	PCM; Thermal energy storage (TES); Thermally activated building systems (TABS); Radiant wall
[54]	Shape change shading	Technology, Material e/h/j/l/m/t	Reactive façade system, temperature regulation, SCM
[55]	Auto-reactivity, Materials, facade components	Materials State-of-Art n/t/u	Innovative; Adaptive; Passive; auto-reactive systems; input-Energy and output-Strategy
[56]	Autoreactive components in double skin façades	Technology, energy g/h/j/k/m/n/t/u	Autoreactive components; double skin facades; Adaptive building envelope; closed cavity
[57]	Autoreactive ventilated façade system	Technology, energy g/h/j/k/m/n/t/u	Autoreactive building component, TEM, thermocylinder, building façade, ventilation system
[58]	Hygroscopic autoreactive building skin	Technology, Material e/j/l/q/t/u	Hygroscopic material, reactivity in wood veneer, biomimicry of façade components, autoreactivity
[59]	Energy efficiency, building skin	Technology State-of-Art e/h/j/k/m/n/t/u	Innovative technologies; Variable Property Materials VPM: TIM, PCM, Dynamic gel; Variable Conductance insulation VCI, Aerogel, Dielectric glass; Variable Transmittance Glass VTG, Variable Convection Diodes VCD, Chromogenic glass, Prismatic panes and films; Dynamic Trombe Walls; Shading systems.
[60]	Integral Façade Construction, curtain wall	Technology State-of-Art h/j/k/m/n/t/u	Integral Facade; Systematic design; Product levels; Supporting functions
[65]	LCA of dynamic BIPV	Technology, LCA, Energy j/k/n/q/r/t/u	Building-integrated photovoltaic system (BIPV); Adaptive solar facade (ASF); Actuator
[70]	Interactive, responsive, adaptive architecture	Technology e/g/i/j/l/m/t/u	Interactive systems, adaptive systems, responsive systems, biosystems, smart materials, bio-materials, networks, artificial intelligence, climate responsive
[71]	New materials	Materials State-of-Art e/g/i/j/k/l/n/t/u	PCM, Alloys, Thermobimetals, AM alloys
[72]	Multi-purpose materials	Materials State-of-Art e/g/i/j/k/l/n/t/u	Thermobimetals, AM alloys, AM polymers
[73]	3D printed facade	Technology, Material e/g/j/l/n/t	3D printed components, multifunctional façade systems
[75]	3D Printed Reversible Shape Changing Components	Material q/t	Stimuli responsive materials; Reversibly actuating components; Shape changing components; Shape memory polymers; Hydrogels; 3D printed components
[117]	Synthetic biology, biomimetic materials in architecture	Materials State-of-Art e/g/i/j/l/n/t/u	Self-healing membranes, thermoregulating materials, SM, bio composites, bioplastics, electroactive materials, synbio materials
[120]	Wood-based responsive building skins	Technology, Material k/t/u	Wood based responsive; Hygromorphic materials; responsiveness; Reactivity; Actuation capacity; Durability; Sustainability, Aesthetics; Weathering

[1] For SAS list refer to Figures 1 and 2.

Table A2. Literature review on ABTs: sources and method.

Ref.	Year	Keyword Combinations	Database/Source
[4]	2016	Adaptive architecture, kinetic, design	University Library TU Munich
[5]	2016	Kinetic, autoreactive, reactive, parameter, building skin, biomimicry	Research gate
[6]	2016	Adaptive, autoreactive, architecture, building skin, material	Research gate
[8]	2013	Adaptive, building shell, façade, responsive	Science direct
[10]	2015	Adaptive, façade, building skin, envelope, high-tech	Google/COST TU 1403
[11]	2016	Dynamic, adaptive, building envelope, technology, kinetic, facade	Research gate
[12]	2017	Dynamic material, adaptive façade, biomimicry	Google scholar
[13]	2017	Adaptive façade, technology, behaviour, movement	Google/TU Delft
[28]	2017	Biomimetics, building envelope, adaptation, architecture design,	MDPI
[40]	2007	Smart material, architecture, design	Google
[41]	2012	Building envelope, design, comfort, active	Google/TIB Leibniz Information Centre
[42]	2011	Façade, kinetics, architecture	Google
[43]	2015	Material, smart material, actuation, change, actuator, robotic material	Science
[44]	2017	Building façade, system, innovative technology	Research gate
[45]	2017	Façade, integrated design, framework, technology, building envelope	Science direct
[46]	2012	Building, high-tech, system, architecture, sustainable, facade	Science direct
[47]	2012	Façade, system, architecture, category, sustainable	Science direct
[48]	2017	Facade, technology low-tech, material, multifunctional	Google
[49]	2017	Technology, building, indoor, energy	Science direct
[50]	2011	Materials, adaptive, active, dynamic, multipurpose, catalogue, classification, robotic	Google/Fraunhofer IRB
[51]	2015	Adaptive façade, building envelope, responsive, classification	Research gate
[52]	2017	PCM, building component, technology, performance, building	MDPI
[53]	2017	PCM, building system, comfort, material	Research gate
[54]	2011	Architecture, skin, building, façade, adaptive, design, intelligent, regulation	Google
[55]	2017	Autoreactive, façade component, material, catalogue	Research gate
[56]	2017	Autoreactive, skin, adaptive, building envelope	Research gate
[57]	2018	Façade, adaptive, technology, low-tech, material	Google
[58]	2015	Responsive architecture, passive, actuation	Science direct
[59]	2012	Building skin, sustainable, multipurpose	University Library Sapienza Rome
[60]	2013	Façade, product, sustainable, comfort, system, technology	Research gate
[65]	2016	Dynamic, life cycle, envelope, adaptive	Science direct
[70]	2014	Adaptive architecture, reactive, biomimicry	Google
[71]	2010	Smart material, architecture, design	Google
[72]	2011	Smart material, architecture, design	Google
[73]	2017	Multifunctional, façade, system, regulation, 3d printing	Google/TU Munich
[75]	2016	3D printing, material, component	Nature
[117]	2018	Adaptive design, technology, sustainable, design, material, biomimicry	Intech open
[120]	2017	Material, responsive, façade, architecture, sustainable	Research gate

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