What do Circular Strategies Mean for Current HVAC Systems in Utility Buildings?

AN EXPLORATORY RESEARCH

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TU Delft

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Preface

As a civil engineer foraying into management studies for construction, I was intrigued at the thought of how structures are realized in the real world and was certain to explore this prospect. Little did I know that what I chanced upon as a buzzword would drive the second half of my Masters. As I learned about the circular economy in various aspects of society and then grasped its relevance in building services, I was determined to do something related to it as it was exciting, new, and upcoming.

My decision to research how circularity can influence HVAC systems stemmed from a conversation with a friend as we complained about how summers are hotter than ever and how there is no air conditioning. This sparked a deep dive into these systems and their impact on the environment was quite astonishing. What reinforced my interest in this topic was K&R which specializes in MEP systems for buildings and is committed to designing solutions that are not only efficient but also sustainable. Their zeal to explore circularity for MEP systems steered my process to identify a potential topic for research. Since then, it has been a whirlwind of a journey with takeaways and experiences beyond the academic realm.

I would like the opportunity to thank my TU Delft Graduation Committee for their unwavering support and guidance throughout my journey. To begin with, I am grateful to Magchiel, my first supervisor, for brainstorming with me, asking me to explore directions, and telling me to take it easy. His words are always reassuring and always manage to calm me down. Erik-Jan, my second supervisor, was a pleasure to work with. I am indebted to him for his advice and that he was always around. “Let me know whenever you need help, I am here.” I held on to these words dearly and I am very appreciative of his insight. He pushed me throughout and I couldn’t be happier. Finally, Professor Paul Chan always offered clarity of thought. He pushed me to think more creatively, and his anecdotes were always layered with the years of experience he has. He nudged me to be patient and let the answers develop organically. I cannot think of a better committee, a blend of all disciplines, with lessons that are sure to stay.

Furthermore, I am extremely grateful to K&R’s Frederik Brink and Ritika Utmani for all their expertise and guidance. Firstly, I was able to learn so much from Frederik, not only the technical aspects of this industry but also the workings of an organization. We have had the most intense discussions where he encouraged me to think of different, innovative solutions and perspectives that added so much value. With Ritika, I am indebted to her for being my constant soundboard, for giving me tips, telling me to take time for myself, and for her instantaneous feedback. Finally, both Frederik and Ritika went out of their way to connect me with stakeholders for interviews, in the summer which helped me stay on track. I had a lot of fun working with the rest of the team of K&R who were all so helpful and made me feel like a part of the team.

I would be remiss to not thank my friends from TU Delft and back home! Finally, I would like to thank my parents, Sunita, and Jagadish for always letting me be myself, encouraging me, and telling me everything is going to be okay. Thank you for teaching me empathy, kindness, and resilience. I could not have done this without you. I would like to dedicate my thesis to you, *Aai and Pa!*

Mrinal Patil

Executive Summary

Introduction

The decision of the Paris Agreement of 2015 and climate goals deliberated upon in 2019 has intensified the requirements for reduction in GHG emissions at both European and national levels. The construction and building sector play an important role in this context as it represents forty percent of Europe's energy demand and is responsible for over 35% of total waste generation. It also accounts for about 50% of all extracted material (Commission, n.d.). This is primarily due to the linearity of business models and the economy which follows the take-make-dispose approach.

Moving away from the current linear economy towards a circular economy is a solution that can alleviate the pressure on the resources. In a CE, economic prosperity is decoupled from resource consumption and the notion of waste is eliminated by maintaining products, components, and materials at their highest value (Foundation, 2013). Recently, this concept has received widespread attention from both academia and policy measures. Even major organizations like Philips and IKEA have committed to sustainable development. However, despite such proactive measures, the realization of a CE in practice has been rather limited and still appears to be nascent (Ghisellini, 2016).

Furthermore, CE is still vague in terms of its terminology and concept which curtails its implementation. The CE has been referred to as a catch-all philosophy (Whalen, 2018) which consists of a multitude of different dimensions (Kirchherr, 2017) and is interpreted differently by different actors (Blomsma, 2017). This is also true for the application of circularity in building services, including HVAC systems in the built environment. HVAC systems are the most consuming service worldwide and have become almost essential due to the demand for thermal comfort, considered a luxury not long ago. However, the application of CE principles to these services is limited despite their significant GHG emissions and high embodied carbon and represents a big economic and environmental opportunity (Croxford, 2018).

The aim here is to realize how the HVAC systems industry can incorporate circular practices. As mentioned before, circularity is interpreted differently and has different dimensions which can be perceived as complex and confusing. Hence, despite the awareness to become sustainable and adopt circular practices for HVAC systems, it may feel like an abstract concept, with countless definitions and strategies. This could be an overwhelming decision-making process and decelerate the transition to circularity. Understanding current HVAC systems and functional examples to apply circular strategies through literature review and interviews can help catalyze action by conveying the idea of a circular economy for building services. This report offers a concise starting point and streamlines the path to circularity by attempting to answer the following research question.

"What do circular strategies mean for current HVAC systems in utility buildings?"

Methodology

To establish the baseline; the current state, system, and process, it was necessary to interview stakeholders from the industry. They revealed their interpretation of circularity, efforts being taken to make the transition, and what are the reasons for the slow realization of this objective in projects.

Based on the assessment of the current state and existing barriers, the researcher could recommend solutions.

Considering the exploratory nature of research where not much is known, thematic analysis is a flexible and useful research tool that provides a rich detailed, and nuanced account of the data collected (Braun V, 2006). It involves the search for an identification of common threads that extend across the interviews conducted (DeSantis L, 2000). This was ideal for this study as the researcher aimed to identify, analyze, and report trends within the data (Braun V, 2006).

Results

The primary aim of the research is to identify circular strategies that can be applied to current HVAC systems and learn of the potential benefits, trade-offs, and level of feasibility of application. This research maps strategies across the lifecycle of the project and informs the influences they have on current systems. However, while the list is a comprehensive set, the researcher does realize that there are several other possibilities to apply circularity principles and intends to provide a flexible, simplified guideline explaining its application and consequences. The decision to include a limited albeit comprehensive set of strategies was to bring order to chaos. It bridges the gap of transition and offers a stepping stone to exercise circular interventions.

Discussions with interviewees also revealed that there is potential to apply circularity, but it is a complex endeavor. All the stakeholders agreed that there is a lack of knowledge on many fronts. The availability of alternatives to conventional systems and their implication on factors like cost, lifespan, and maintainability is a major cause of apprehension. Furthermore, the lack of knowledge sharing, and collaboration was also significant. The interviewees made important recommendations regarding the need to collaborate with more partners and added functions to their expertise to promulgate the transition. They also put forth strong ideas that contributed to the identified circular strategies and recommended changes needed throughout the lifecycle of the project to render their application feasible. Regarding the consequences of circular interventions, several benefits and compromises came to light. Throughout the interviews, it was acknowledged that while the strategies recommended do carry potential and that the possibility of application does look promising, implementation could be impeded due to a lack of information about equipment and availability of expertise. This is why the influence of a few recommended strategies on performance evaluation criteria could not be determined. However, the final product does account for these nuances by identifying their level of feasibility that can be enhanced as the market, regulatory frameworks, and technology evolve. Moreover, the research also identified what it means to be circular by providing a set of strategies employing both prevalent and unconventional practices that can be implemented. Another significant finding was the strong influence of the location, functionality, and climate on the effectiveness of circular strategies. This implied that some of the relationships derived are project-specific and can be realized only if exercised. Lastly, they all agreed that stronger legislative reforms and guidelines can augment their motivation to further into this concept.

Lastly, this report is intended for an MEP consultant who can utilize the product developed to recognize possible interventions and what these choices entail. It is an attempt to bridge the knowledge gap and the simplified representation of both strategies, and their impact renders it usable for the consultant to refer to as a guideline and provoke a thought in this direction. Moreover, the categorization of strategies based on feasibility is an outcome of interviews to offer a more actionable roadmap for consultants and clients who seek to incorporate circularity in HVAC design. This allows the allocation of resources in strategies that are realistic to apply in their specific projects. The consultant is now apprised of alternative options and if they are flexible and receptive, they can exercise it to aid their client in making choices that conform to the principles of circularity and sustainability and meet project requirements. Moreover, practical implications for current HVAC systems offer more tangible and relevant insights to industry professionals and can assess the resource requirements of incorporating circularity in their practice.

The final product includes a comprehensive list of circular strategies mapped to specific lifecycle phases; and a reference tool available to the MEP consultant (Figure 21: Modified Lifecycle-Circular Strategy Mapping). Additionally, it outlines the impact of each strategy on performance evaluation criteria used to assess HVAC systems. These strategies are organized in descending order of feasibility, denoted from A to C (Table 5: Circular Strategies with High Feasibility (A)Table 6: Circular strategies with medium feasibility (B), and Table 7: Circular strategies with low feasibility (C)

Collectively, these components form a systematic approach consisting of three essential steps and are illustrated below. This approach leverages the provided information to achieve the following objectives: developing circularity ambitions, selecting circular strategies that conform to the project requirements, and owner's goals, developing circular installations for HVAC systems, and achieve SDG goals.

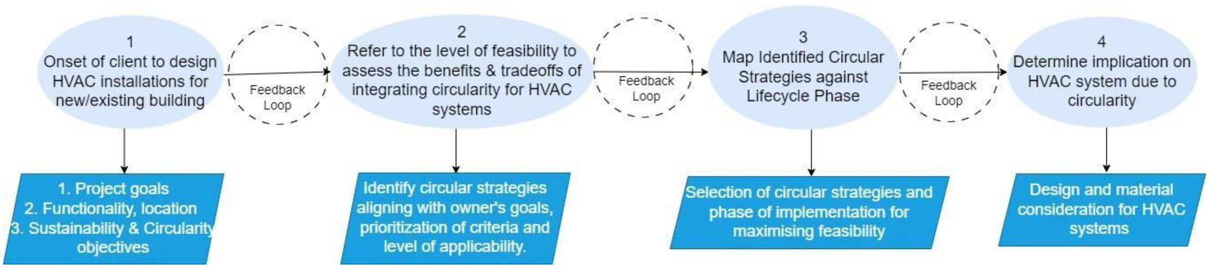

Figure 1: Approach to integrate circularity principles for HVAC installations: A Decision Support Framework

There is still a long way to go to embed the principles of circularity for building services, this report is just an effort to mark the shift and instill a thought to move from linearity to a more circular practice.

Limitations and Future Work

This study was exploratory and employed qualitative methods. The employed research design leaves room for bias and differing results in case the study was conducted by another researcher. The perception and interpretability of the interviewees also affect the research outcome. Also, the recommendations made by the researcher are derived from suggestions made by interviewees and the researcher's analysis which can be used as an initial step/reference a consultant can use to design solutions. They are guidelines, to be used by the consultant and the client to explore further avenues that are more suited to their project requirements.

For future work, the researcher strongly recommends exercising the framework on actual cases to investigate the feasibility, accuracy, and practicality of the framework. It is highly plausible that additional research might be required to conduct a deeper analysis and more comprehensive research to make it useful for practice.

Another noteworthy recommendation is to study further performance evaluation criteria that can be included to assess circular HVAC systems to realize their full potential and inform of more consequences that were not explored in this research.

This study only encapsulated the relationships between circular interventions and performance. It would be highly beneficial if future work was committed to quantifying these relationships for more tangible results that can significantly help in decision-making.

Lastly, considering the popular opinion among the stakeholders was the need for more regulations regarding circularity for businesses, it would be interesting to study what actions can be taken for policy reform to accelerate the transition not just for building services but the entire built environment.

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1. Introduction

The construction industry makes up one of the largest contributors to the global economy and employs about 7% of the world's working population. (Acharya & Finch, 2018) However, it is also infamous for being one of the largest consumers of resources and was responsible for about 40% in the 1990s. (Rees, 1999) The number has increased manifold due to the rapidly growing population. Moreover, this industry is now responsible for 50% of global raw material extractions and over 35% of global waste generation (V. Goswein, 2022). This industry is also energy intensive and generates carbon emissions in the range of 25-40%. These numbers are due to the "take-make-dispose" model rampant in the construction sector (EMF, 2015). Despite the European Directive of 2008 requiring 70% of the building waste to be recycled or reused by 2020 (General, 2018), resource efficiency and planning have not been prioritized enough. This approach has led to significant structural waste and exhausted resources.

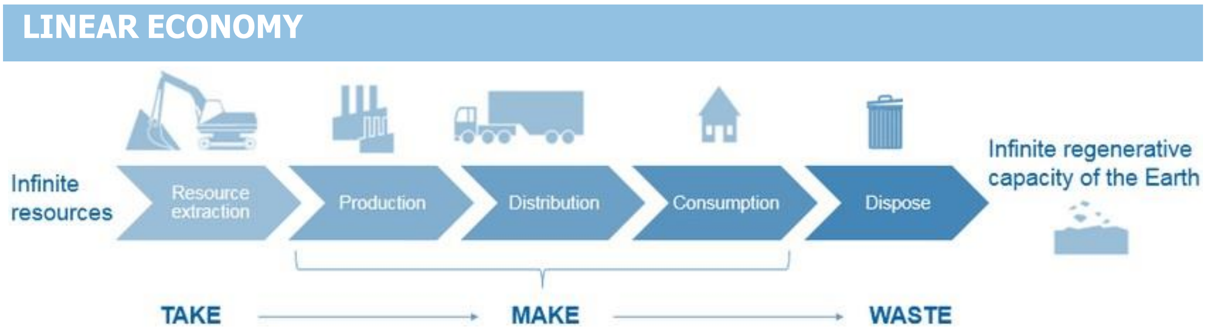

Figure 2: Linear Economy (Wautelet, 2018)

Given the profound impact, the EU's action plan for a circular economy is pivotal to curb the environmental impact and energy consumption as well as reduce waste generation by maximizing reuse and recycling rates (Honic, 2019c). The Ellen Macarthur Foundation has been actively promoting the potential of a circular economy and has defined it as a "*regenerative system that aims to keep materials in a closed loop at their highest value"* (EMF, 2015)

In a circular economy, materials, products, and their components are managed in loops to retain their highest value (Acharya & Finch, 2018). Business models encompassing the concept of Circular Economy warrant the reuse of end-of-life building materials and posit the deconstructed parts and components as material banks for new buildings (Hopkinson, 2019). This concept still needs time, especially in an industry that is slow to embrace innovation.

This industry is characterized by unique projects with a complex value chain (Pomponi, 2017). The transition to a circular economy will require systems thinking and new strategies for the entire building life cycle and the value chain.

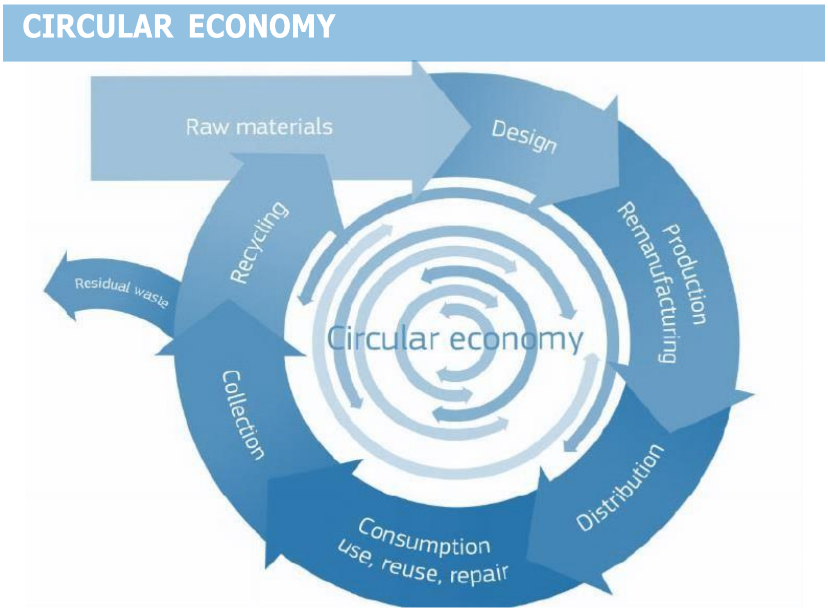

Figure 3: Circular Economy (Urbact, 2016)

1.1 Problem Definition

Buildings constitute a significant portion of the built environment and represent about half of the construction sector (Graaf, 2022). However, the environmental impact of the sector is set to catapult as the global population is set to skyrocket to almost 10 billion by 2050 (Val, 2023). The increasing population will propel demand for buildings, resources, and materials which will be detrimental to the environment and the population (Graaf, 2022). Additionally, about 85% of the existing building stock in the EU was built before 2001 and 85-90% of the buildings that exist today will still be upright in 2050 which will have repercussions (Graaf, 2022). For instance, interiors and building installations may consume more energy due to their obsolescence and inefficiency (Energy U. , 2019). Damaged building services and outdated floors may affect comfort and indoor air quality. Poorly insulated ceilings, walls, and roofs can increase energy consumption and contribute to greenhouse gas emissions for heating and cooling. It implies lower energy efficiencies and calls for critical interventions in terms of design and material selection, and strategic consideration for buildings in the end-of-life stage (Graaf, 2022).

This is also true for building services i.e., mechanical systems, plumbing, and electrical systems including heating ventilation, and air-conditioning services, an important aspect of a building's functionality. Building services face detrimental issues like high front-end investment, recurring maintenance, fast obsolescence, and performance gaps (Croxford, 2018). These factors amount to a significant life cycle cost. (Cheshire, 2014). They account for substantial emissions throughout its life cycle like raw materials extraction, manufacturing process, construction use, and end-of-life disposal (Cheshire, 2014). Moreover, there has been an increased focus on emissions during operations and embodied energy has been neglected. CIBSE Research Report 9 estimates that 2% to 25% of the initial embodied carbon is due to building services and that it continually increases with time due to high maintenance and a shorter life span (Hitchin, 2013). Building services systems play a key role in the total life cycle emissions and operating expenses of buildings. Building services are now in a "golden spot" for implementing circular economy principles due to this and the performance gap between designed and installed MEP systems (Croxford, 2018). However, this layer of the built environment is under-researched for circular economy implementation (Croxford, 2018).

Particularly, installations for HVAC systems represent about 1/10th of the total building value and 2/3rd of all building services. The number is relative depending on the configuration of HVAC systems and the materials used for wiring etc. (Hitchin, 2013). Also, the HVAC systems are a major contributor to the number of metals in a building (Oosting, 2021). There is a scarcity of primary materials, low material efficiency, and a high demand for replacement of systems. They also consume a lot of energy and are responsible for 20% of global electricity use (Khosla, 2020). Not only that, but they also affect the outdoor air quality and noise levels through exhaust gases thereby disturbing the quality of life and biodiversity (Ambrosetti, 2022). Cumulatively, these systems result in a significant impact and call for circular strategies for HVAC building installations.

The HVAC segment is still lagging in terms of circularity compared to the rest of the construction industry (Oosting, 2021). Furthermore, it is characterized by a complex, fragmented supply chain and involves products supplied by third parties (Oosting, 2021).

The challenges faced by this industry are conducive to aiding a paradigm shift towards more circular thinking and design. However, this industry is characterized by a complex supply chain network with many stakeholders, and they need actionable insights to push for a transition towards circularity. Clients and building owners can be frontrunners in driving the course for circular thinking and business models throughout the life cycle of the project but need knowledge and advice from practitioners.

Additionally, if these stakeholders do want to include circularity principles in their project for HVAC systems and by extension, the services layer, the market is still quite linear. The availability of circular options or alternatives to current HVAC systems is limited. The limited availability also translates to higher costs and evokes hesitation to invest in such principles. In essence, a transition to a circular economy requires a transformation of the whole supply chain behind the building services and components (Croxford, 2018).

To increase the uptake of circularity for HVAC systems, the stakeholders are to know what the ways are to incorporate it and what are its consequences. Croxford also iterates that there certainly is a knowledge gap around the decision-making process involved in the design of circular building services. To give an example of a stakeholder, an MEP consultant needs to know of the alternatives/circular options to replace current HVAC systems and how can they be applied to advise/persuade clients to invest in them. This is why this report is intended to create guidelines for an MEP consultant based on criteria used to assess HVAC systems.

Additionally, it is important to know if the circularity principles were to be integrated, and what would it mean for the current HVAC systems and the building. While it is evident that circularity principles can greatly reduce emissions and enhance resource efficiency, it is essential to know if they meet the objectives of these systems. It is also crucial to question the implications of their integration on the lifecycle process of these systems. For the same, it is vital to understand the current systems, and the deficiencies in them and map the impact of circular interventions. To realize their effectiveness and if they are context-dependent or project-specific requires the main research question to guide this study.

1.2 Research Question

This research is qualitative and an exploratory study aiming to realize how circularity principles can be integrated into HVAC systems for utility buildings and how they fare against current systems. For the same, the research arrives at the question below.

"What do circular strategies mean for current HVAC systems in utility buildings?"

The sub-research questions mentioned below are the building blocks that help answer the main research question.

1. What is circular economy and what are the existing frameworks for the built environment?
2. What are the configuration and components encompassing HVAC systems and what is the current level of implementation of circularity?
3. What stakeholders are involved in the lifecycle of HVAC systems and what role do they play in the industry?
4. What are the barriers and opportunities specific to the integration of circularity in HVAC systems?

These questions create a systematic path to answer the main research question. It is imperative to know the principles of circular economy and the frameworks that exist to implement them before understanding how they can be applied to the HVAC systems industry. The next question then delves into identifying the systems and components constituting these installations to know the potential for circularity and understand the criteria used to assess these systems. These criteria form the bridge to know how circularity influences these systems. Considering the qualitative nature of the research, this study involves interviews. Identifying the key stakeholders is essential for gathering comprehensive insights. Additionally, given the integration of circularity principles requires a transformation of the entire supply chain, understanding their roles becomes even more significant and enables exploration and identification of additional roles and responsibilities to facilitate the successful implementation of circularity within the industry. Together, these questions will provide for a more comprehensive outcome.

1.3 Research Scope and Limitations

A research scope needs to be established to determine the boundaries of the thesis and ensure the intended research has a dedicated output within the confines of the established scope.

This study focuses on HVAC systems for utility buildings. Utility buildings are large spaces offices, shops, hotels, restaurants, educational facilities, and healthcare facilities. The International Energy Agency (IEA) reported that this sector accounted for 40% of total building energy use and 38% of total building CO_2 emissions in 2020 (Delmastro, 2022). Another study by the Buildings Journal also concurred saying that these buildings have higher energy and carbon intensity due to their higher annual heating and cooling loads, larger floor areas, higher internal gains, longer operating hours, and stricter control requirements (Al-Waked R. N., 2017). Additionally, this study is being done in collaboration with K&R which has multiple projects like hotels, office buildings, commercial spaces, hospitals, and laboratories they consult on. This implies ample expertise and allows for an extensive number of interviews with the stakeholders involved.

Another important facet of the established scope is the stage in the value chain this study delves into. The figure represents the value chain for HVAC systems. For illustrative purposes, the stages of the value chain are represented linearly. However, some stages do occur simultaneously or in a different order. However, the stages within the ellipse highlight the scope of the research (Figure 4: Scope of Research). Manufacturing and production are not completely within the ellipse signifies the knowledge dedicated within the defined scope of the research does touch upon this stage on account of its immediate influence on the design, construction, utilization, and end-of-life stages. Another significance of addressing this stage is that the researcher deemed it important to interview manufacturers to know of potential circular interventions within their domain and their requirements to facilitate this transition. This is crucial as knowledge of such practices is of relevance for MEP consultants to know how to choose low-carbon alternatives.

While the researcher does recognize the influence of other processes that contribute to the carbon footprint of HVAC systems and these aspects are of paramount importance in the pursuit of sustainability, the selected scope scrutinizes specific lifecycle stages to provide actionable insights and recommendations that stakeholders can feasibly implement. The aim is to offer tangible guidance for incorporating circularity principles into HVAC systems with a focus on design, construction, and end-of-life strategies. Moreover, by addressing these specific lifecycle stages, the minimized need for additional resources through circular practices inherently mitigates the environmental impact of the activities beyond the ellipse.

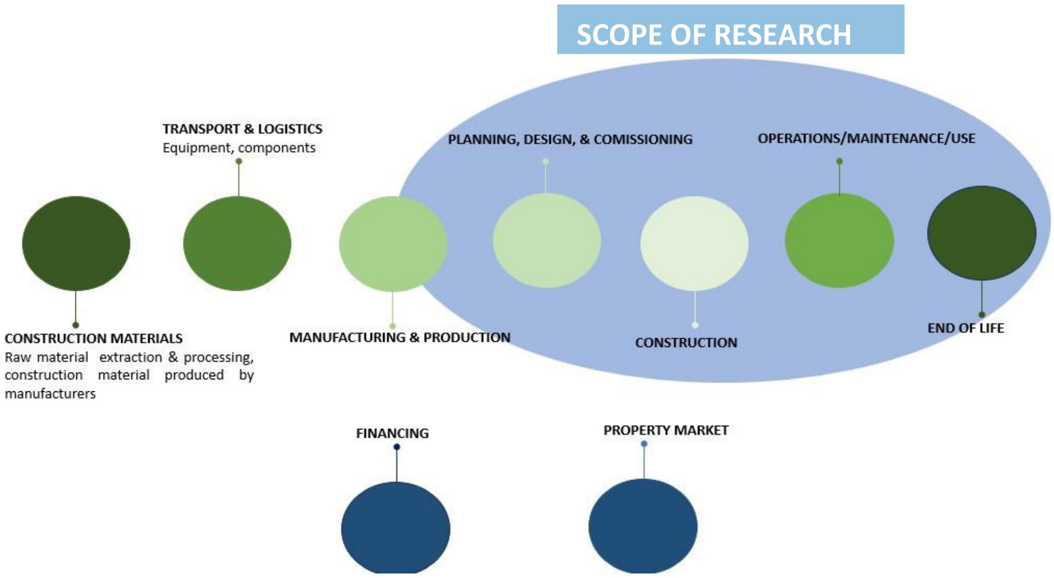

Figure 4: Scope of Research

However, it is important to note that there are not many studies investigating circular options for HVAC systems. As a result, the conclusions and recommendations made by the researcher would be derived from interviews with stakeholders and experts. Lastly, the report is addressed from an MEP consultant's point of view.

1.4 Relevance of Research

The application of circularity principles for HVAC systems holds significant relevance due to its potential to address several key sustainability challenges. Given below are a few reasons why implementing circularity for HVAC is relevant.

1.4.1 Regulatory compliance and policy alignment

The Dutch government has several initiatives aiming for buildings to be circular and sustainable. It has introduced a government-wide program for a circular economy aimed at developing a circular economy in the Netherlands by 2050. The ambition of the cabinet is to realize with a variety of stakeholders the objective of a 50% reduction in the use of primary raw materials by 2030. (Commission, 2016)

Another initiative by BENG requires all new construction, both residential and non-residential to comply with the requirements for near energy-neutral buildings to be able to apply for the environmental permit (Nederland, 2023).

The European Commission adopted the new circular economy action plan (CEAP) in March 2020 which forms one of the main building blocks of the European Green Deal. The action plan announces initiatives along the entire life cycle of products targeting their design, boosts the circular economy process, and encourages sustainable consumption (EU, 2023).

These initiatives offer a huge impetus for transition towards circularity especially for systems that contribute significantly to the emissions generated from a building. They also offer recommendations and factsheets that can urge businesses to adopt circularity as their guiding principle.

1.4.2 Emissions and Waste Reduction

Circular practices aim to reduce waste generation by promoting reintroduction of materials and components back into the cycle thereby also reducing the demand for primary materials. Moreover, the prices of raw materials have been rising in the last ten years and are expected to rise again. This can drive attention toward the secondary market (Lucia Mancini, 2013).

1.4.3 Climate change and population

HVAC systems have become almost essential in parallel with the spread of the demand for thermal comfort. Population and urbanization are boosting energy use and higher affluence affords better comfort levels. This increases their impact manifold and with harsher summers and winters, it increases the heating and cooling demand which further increases energy use. This is why it is essential to design energy-efficient HVAC systems designed for longevity (M. González-Torres, 2021).

1.5 Research Method

This project requires a thorough understanding of the current systems and practices, which can be recognized best through interviews with the stakeholders of the industry. These interviews would offer insight into their understanding of circularity, what measures are being taken by them, and recognize the impedance of transition. This establishes the base line and appropriate recommendations can be made.

The data would be gathered through semi-structured interviews that are anonymized to uphold the privacy of individuals. The decision to adopt this methodology is motivated by the exploratory nature of research that might be curtailed if there is a strict protocol leaving no room for flexibility and rapport building. The data collection process seeks to amass strong opinions, requirements, and expertise to be able to develop a credible, practical, and feasible framework.

The interviewees would be several stakeholders from the HVAC industry to get a holistic overview of the process and understand various perspectives and priorities. This is crucial to understanding the landscape and creating a product with due diligence to all narratives. Even differing perspectives are key to observe as they help recognize potential barriers.

1.6 Research Outline

This report consists of four main sections that have been elaborated below.

Phase 1: Literature Study

This section provides a theoretical foundation describing the circular economy, its principles, and relevant concepts required for research. It is then followed by understanding the components and systems commonly comprising HVAC systems and the lifecycle of these installations. This section also lists the performance evaluation criteria used to assess these systems. Together with circular economy principles, a framework based on literature can be developed.

Phase 2: Methodology

The theoretical background established through the literature review forms the grounds for the next stage to garner primary data to investigate how circularity can influence HVAC systems. A thematic analysis of the interviews conducted would help deduce themes that can function as building blocks to further develop the framework.

Phase 3: Data Analysis and Results

This phase unveils the findings from the interviews to improve the literature-based framework and identify barriers and opportunities corresponding to circularity interventions for HVAC systems. The latter section links circularity with performance criteria to know the implications and feasibility of circularity.

Phase 4: Conclusion

This section of the report discusses the findings from the interviews and draws inferences from the conducted study along with its limitations and recommendations for future work.

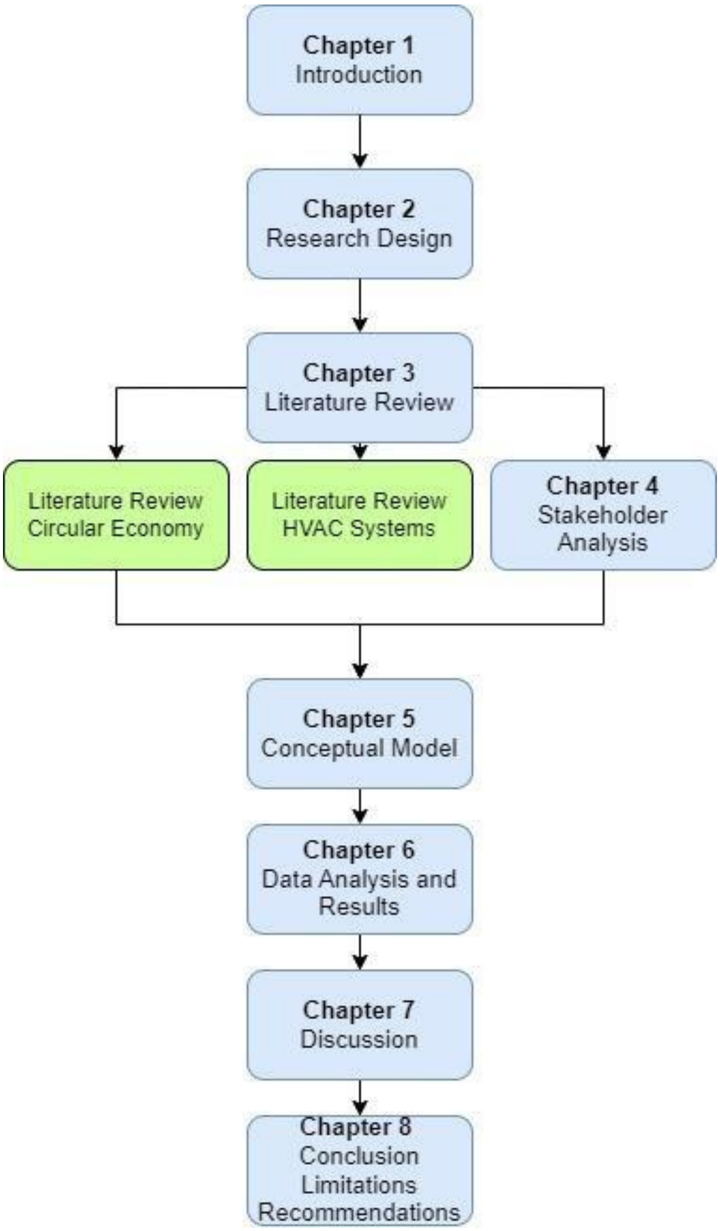

Figure 5: Research Outline

2. Research Design

This chapter describes the methodology used to arrive at concepts and solutions. The following sections discuss the research and data-gathering methods followed by a description of how the data collected is to be analyzed.

2.1 Research Methodology and Data Gathering

This research employs two methods, secondary research through literature study and collection of empirical data through interviews with stakeholders of the industry. A comprehensive literature review aimed to answer sub-research questions, 1, 2, and 3. This was followed by a qualitative research method employed to garner primary data. For the same, semi-structured interviews and an expert validation process was conducted to answer sub-research question 3 and 4. Finally, findings from the interviews were used to build upon the findings from the literature review to answer the main research question.

The figure below is a schematic view of the research design process considered. The solid lines represent the chronology of the sub-questions answered while the dotted lines represent the origin of the input.

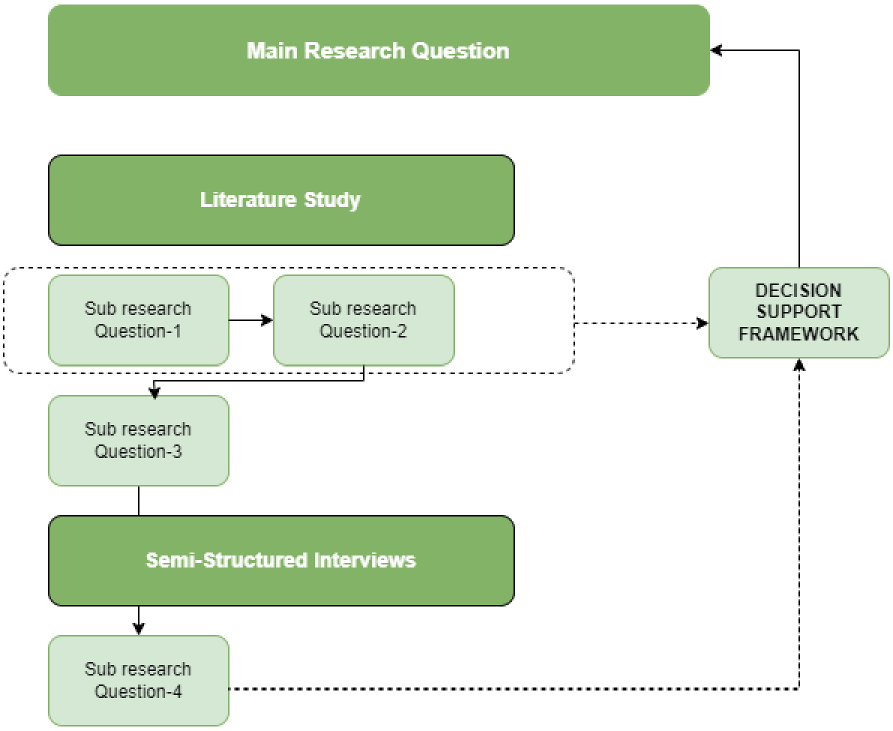

Figure 6: A Schematic representation of methodology for research questions

Subsections **2.1.1 Literature Study** and **2.1.2 Semi-structured Interviews** justify the choice including an explanation for the approach chosen and interview protocol. This is followed by **2.1.3 Expert Panel** and finally, section **2.2 Data Analysis** describes the method adopted for data analysis.

2.1.1 Literature Study

This research required a clear understanding of both bodies of work. The first is the principles of circular economy and the various frameworks that are currently used. Secondly, it was essential to study the commonly used systems encompassing HVAC installations and the process employed to install them in buildings. Finally, theoretical understanding and identification of the stakeholders involved would help analyze how they can play a role in the transition. This laid a strong foundation to build a decision support guideline and identify the potential for circularity in HVAC.

As mentioned before, the literature review aimed to answer sub-questions 1, 2 & 3 and create a **5. Conceptual Model** that could form the basis for conducting an empirical study. Circular strategies were mapped against lifecycle phases through analysis of papers available on Google Scholar, Scopus, ScienceDirect, and websites like Ellen MacArthur Foundation, Circle Economy, and ARUP.

2.1.2 Semi-structured Interviews

This section of the study focused on the roles, and interests of the identified stakeholders and their perception of integrating circularity in HVAC installations for utility buildings. This approach was intended to understand the barriers and opportunities the proposed integration entails which can then be accounted for, to ultimately develop a comprehensive decision support framework that links both.

Garnering data from actors in the field would support this study from a practical standpoint. Understanding their roles, interests, and perspectives required a qualitative analysis which is why a method of semi-structured interviews was adopted.

The nature of the research is exploratory. There is limited knowledge about the integration of circularity in HVAC systems and the open-ended format of this qualitative data collection method was congenial in understanding the attitudes, complexities, and experiences of the interviewees who are significant in the industry (Crinson, 2016). This line of questioning is the best of both worlds of organized and unstructured interviews since it allows for comparable, reliable data and an avenue to ask follow-up questions (Salome, 2022). A semi-structured interview is characterized by an interview guide developed by the researcher that contains major questions or themes that are used similarly in every interview but make room for probing questions and other means of inquiry not limited to the developed guide (Crinson, 2016). It provides an opportunity to identify new ways of seeing and understanding the topic at hand (Cohen D, 2008).

Location of interviews: The mode of conduct of these interviews was in-person meetings or online meetings. Online meetings would take place on Microsoft Teams or Zoom.

Duration: Each interview would tentatively last for 45-50 minutes. The stipulated duration allowed for the open-ended nature of questions and gave enough time to build a rapport.

2.1.2.1 Interview Protocol

An interview protocol is developed by the researcher to offer structure and create a list of topics that need inquiry. The curated questions are kept open-ended to elicit more information.

The interview guide is composed of the following sections curated as follows.

- **Introduction:** The interview starts with an introduction of the interview and addresses the research objective, purpose of the interview, agenda, and informed consent. The participant must be briefed well (Wilson, 2014)

- **Themes:** The purpose of the interview is addressed here and is composed of four themes preceded by a context that includes questions about the role, qualifications, etc. of the participant. **Theme 1** is general questions about the organization, decision-making, and collaboration followed by **Theme 2**- circular economy, its awareness, and current implementation. **Theme 3** addresses circularity in HVAC systems; barriers and opportunities and finally **Theme 4** has questions about the inclusion of circularity in HVAC; steps and measures.
- **Closing remarks:** For further questions and feedback.

Questions drafted for each stakeholder along with the comprehensive interview guide have been included in Appendix A.

2.1.3 Expert Panel

Post interviews, the guideline was developed and shown to an expert; a circular building installations consultant, asking for their feedback or any recommendations they have, to improve the functionality of the guideline. The objective of the validation process was to know if it could help the industry pick up the pace for circularity in HVAC and if the guideline served as a good starting point to do so. There was a discussion that followed which involved brainstorming for modifications or addendums that could be explored further.

2.2 Data Analysis

The literature review revealed strategies and recommendations to improve the lifecycle process for HVAC systems that were then analyzed to provide strategies to implement circularity. Thereafter, interviews conducted revealed themes about **collaboration, barriers, opportunities, and performance** of circularity which were analyzed to yield findings and finally render a complete framework. Therefore, a thematic analysis was conducted to render findings from the interviews. Thematic analysis is qualitative and useful in analyzing and presenting themes related to data retrieved from interviews. It is useful to discover insights using interpretations and to find patterns of data that can address the research (Alhojailan, 2012).

The **2.1.2.1 Interview Protocol** was developed based on research questions and theoretical concepts derived from literature. The interview sessions produced data and each transcript was analyzed and outlined. Segments of texts were coded and clustered both inductively and deductively. The four themes of the interview were predefined codes and inductive codes were assigned to clusters of data that were either separate from the predetermined codes or expanded from the protocol. The codes were then connected, and themes were identified as **first-order themes**. They were then further clustered under overarching themes that formed the **second-order theme** (Jennifer Fereday, 2006). An example of the entire process followed has been included in Appendix B. It illustrates an example where the data was first deductively analyzed under the theme set by the interview protocol -barriers, and first-order themes inductively emerged as they expanded from the protocol -cost, reliability, flexibility, performance, and feasibility. They formed the overarching theme of performance of circularity.

In summary, identification of circular strategies and relevant HVAC examples mapped to their relevant lifecycle phases were identified from literature. Modifications to these strategies, along with their performance and feasibility was an outcome of interviews.

3. Literature Review

The literature review has been divided into three subsections, each focused on the different elements that are to be analyzed further to develop a conceptual framework. It will address the concept of circular economy in the context of the built environment, discuss the need to transition towards a circular economy as an industry and elaborate on the different principles that can be used to make this transition. This is then followed by an attempt to understand the fundamentals of an HVAC System in utility buildings. It includes the configuration of HVAC Systems, their basic components, and the functionality necessary to identify the potential for circular intervention. Ultimately, this section aims to develop a solid ground based on previously done research to build a decision support framework as the end deliverable.

3.1 Circular Economy

It is essential to understand the core of this study, Circular Economy before delving into the application of its principles to HVAC Systems. This allows the identification of circular strategies that could potentially be applied to HVAC systems. Moreover, the influence of these strategies on the evaluation criteria used to assess the performance of HVAC systems in buildings will be understood to realize if and how these strategies can bring about change in the existing systems. These criteria will be elaborated upon in the section focusing on HVAC systems.

3.1.1 Context

Ever since the Paris Agreement, there has been a consolidated effort observed throughout the world to reduce greenhouse gas emissions from energy. The EU has made continued progress and even passed the first-ever European Climate Law that mandates climate neutrality by 2050 (Woolven, 2021). Global trends also show a stark rise in the use of renewables, particularly wind and solar energy. Even so, this is just a part of the equation. Despite such impressive groundwork, the level of greenhouse gas emissions continues to rise. A major contributor is emissions due to the way materials are sourced, used, and disposed of (Woolven, 2021). Businesses and supply chains have been predominantly following the “take-make-dispose” model wherein the materials are extracted, processed to form products, and then discarded at the end of their life generating significant waste throughout the whole process. These conditions require urgent intervention. It is pertinent to tackle all sources of greenhouse gas emissions. A circular economy can be the answer to these problems.

3.1.2 What is a Circular Economy?

Circular economy is a complex phenomenon and various researchers are still trying to define it. Generally, a circular economy is an economic model that favors the preservation of natural resources and the decoupling of economic growth from material consumption over the entire lifecycle of products and services (Gruis, 2022). The Ellen MacArthur Foundation defines circular economy as a regenerative system that aims to keep materials in a closed loop at their highest value (EMF, 2015). A circular economy is about value retention along the whole supply chain and life cycle of a product or a service and designing out waste and emissions from the beginning (Gruis, 2022).

The concept of Circular Economy is an evolving concept and driven by context. The means to becoming circular vary when considering components, products, and buildings compared to the strategies needed for organizations, municipalities, or entire cities. However, regardless of the regime level, collaboration among stakeholders is required to ensure that the social, environmental, and economic dimensions are achieved concurrently (Salvioni, 2020). These objectives require a synchronized effort by the relevant stakeholders towards achieving the core principles of circular economy mentioned in 3.1.3 Key Principles of Circular Economy.

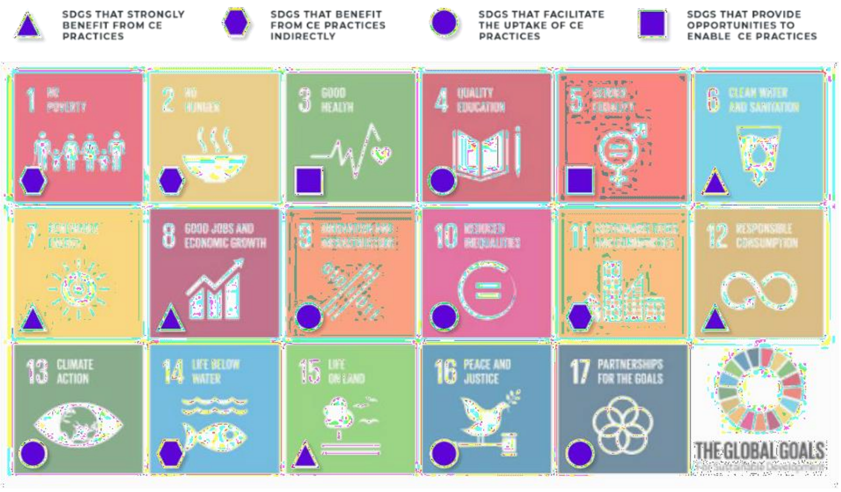

Figure 7: Sustainable Development Goals (Sutherland A. B., 2022)

3.1.3 Key Principles of Circular Economy

The Ellen MacArthur Foundation asserts that the circular economy is based on three key principles (EMF, 2015):

- **Eliminating waste and pollution**: Many products are designed for disposal. Products could be designed to produce no waste and could be refurbished, recycled, reused, maintained, or recycled as a last resort focusing on elimination of waste. This measure can mark the beginning of closing the loop for materials and focus on upstream design. It also stresses the refusal of hazardous substances and pollution of air, water, and soil.
- **Circulating products and materials**: Materials and products can be kept in circulation through two fundamental cycles; the technical cycle and the biological cycle. These cycles can be represented in the diagram famously known as the Butterfly diagram with technological and biological cycles (EMF, 2019).
    - **Technical cycle**: The most effective way to retain the value of products is to maintain and reuse them, with business models based on sharing and resale, and cycles of maintenance, repair, and refurbishment. Recycling is the final step that allows materials to stay in the economy and not end up as waste.
    - **Biological cycle**: Biodegradable materials that cannot be reused can be circulated back into the economy by composting or anaerobically digesting organic materials, regenerating land, and growing more food or renewable materials. Recycling is the final step that allows materials to stay in the economy and not end up as waste.

  Designers must consider how their products can fit into the technical or biological cycles after use. Currently, many products end up as waste since they are created by fusing both technical and biological materials in a way that cannot be separated.

- **Regenerate nature**: It advocates for less land exploitation for extraction of primary materials and lets nature flourish. Additionally, this principle also advocates for a systemic replacement of fossil fuels with renewable sources of energy produced using infrastructure designed for reuse, repair, remanufacture, and recycling.

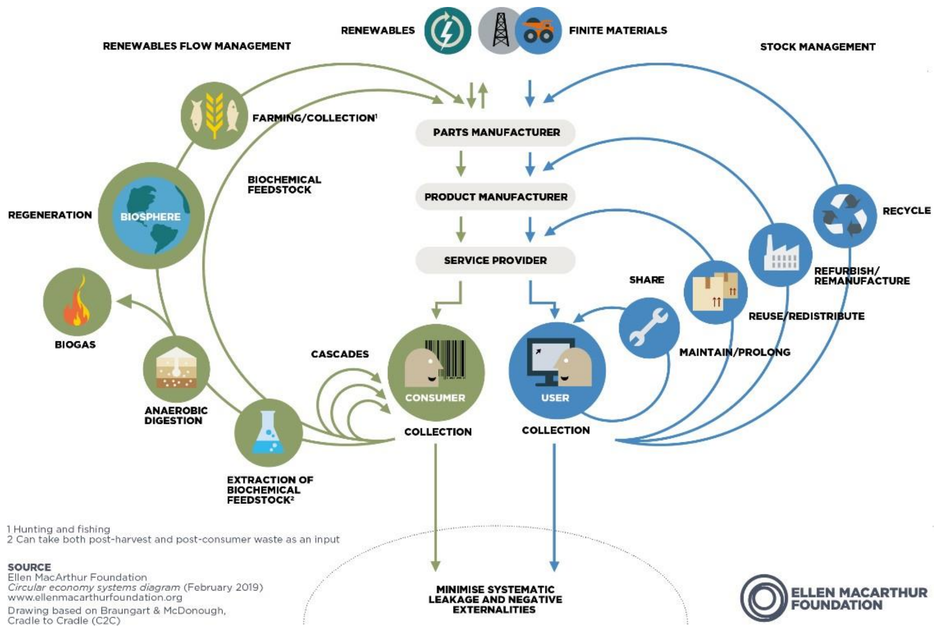

Figure 8: Butterfly diagram with technological and biological cycles (EMF, 2019)

3.1.4 Circular Economy in the Construction Industry

The building and construction sector is a key contributor to the global economy and employment as it makes for about 9% of the EU's GDP (Commission, 2016). However, higher numbers are observed when discussing this industry's environmental impact. It is also one of the highest consumers of resources: about 50% of the total use of raw materials and 36% of global energy use (IEA, 2019) (P´erez-Lombard, 2008). It also contributes to about a third of the total waste generated in the EU (Ghaffar, 2020). These numbers are observed due to the linear economic model. The problems in the construction sector are further exacerbated due to material price fluctuations, scarcity of materials, increase in demand, urbanization, climate change, and inefficient waste management infrastructure (Saari, 2020)

The burden on the built environment will increase manifold as the population is set to grow by about 20% to reach almost 10 billion by 2050 (Nations, 2019). It is also important to consider that about 85-95% of the buildings existing today will also exist in 2050 and a majority of the building stock is over 50 years old implying lower energy efficiencies (Gruis, 2022). This highlights the need to not only be mindful of new construction but also consider the impact of the standing structures. There are a few ways existing building structures can be made more circular (Agency E. E., 2022)

- Increasing the intensity of use of the building by transforming existing spaces with multipurpose areas. For example, office canteens could transform into restaurants in the evenings which reduces space and other resource requirements.
- Delaying building demolition by repairing the structure and thereby reducing the demand for new buildings.
- Deploying maintenance programs and asset management systems to prolong the life of the asset and reduce the rate of replacement.
- Replace resource-intensive physical assets with virtual avenues. For example, online marketplaces for all kinds of products as opposed to retail stores.
- Using nature-based solutions that include roof and façade renovations to install green elements.

Adopting a circular economy approach to high waste and perpetually growing sectors like the built environment presents a tremendous opportunity to realize a greater value and minimize waste by keeping materials in a closed loop. Implementation of circular economy principles could lower industry costs, reduce environmental impact, increase livability, and promote a healthy productive environment (Ghisellini, Cialani, & Ulgiati, 2016).

A transition to circularity in the construction industry requires systemic thinking. It urges an understanding of the life cycle of the building and the value chain, an approach vital for stakeholder integration (Zimmann, 2016). Considering the evolution of CE is still underway, it is essential to gain a comprehensive understanding of the circular practices that have been developed (Munaro, 2020). Their analysis could yield circular interventions that could potentially be applied to HVAC Systems in utility buildings. They have been discussed in detail in the subsequent sections.

3.1.5 Circularity in Buildings

Buildings are seen as complete structures designed for a specific purpose; they intend to serve for about 50-75 years. They seldom offer the opportunity to extend their lifespan despite their long tenure. (BAMB, 2016)). Presently, many buildings are demolished after 20 years citing obsolescence, diminishing the service life, and obliging a faster return on investments. Failure to remove or replace building systems or components results in resource inefficiency, increase in waste, and spatial inadaptability (BAMB, 2016).

Given below is a diagram of a building structure represented by 6 layers (Brand, 1994). This widely known model depicts a conventional structure that comprises separate albeit interlinking layers, each characterized by a different service life.

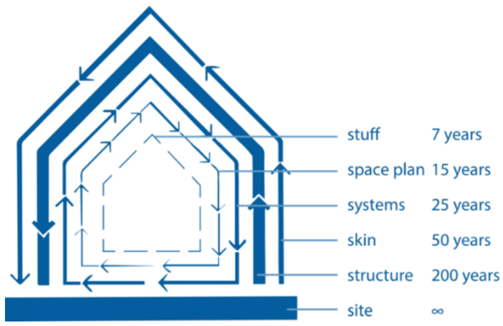

Figure 9: 6S Model (Brand, 1994)

This representation allows for a more adaptable design that can be repurposed and can retain value if not increased. These layers can be instrumental in developing circular interventions and even diminish the need to develop entirely new assets. Describing buildings as discrete layers, each characterized by their lifespan and function gives a new perspective to consider for architects, designers, and other stakeholders involved.

3.1.6 Circular Principles and Frameworks

As mentioned earlier, A thorough understanding of the current principles and concepts concentric with the Circular Economy is necessary given the evolutionary state of this concept (Munaro, 2020). Previously done research has laid down expansive categories and models of circular principles. This infrastructure puts forth many circular strategies corresponding to both design and business models that could potentially be applied to HVAC systems. These models are conducive to arriving at easy, practical, and actionable insights that can be applied to both buildings and systems. This section elaborates on two such models that are widely recognized.

3.1.6.1 10-R Model of Circularity (J. Potting, 2017)

The 10-R model is a comprehensive roadmap to transition towards a circular economy. It consists of 10 principles that promote the efficient use of systems, to reduce waste and regenerate natural systems. They are listed below in decreasing order of grade of circularity with R10 being the most circular and R1 being close to linear economy.

Rethink: Rethinking buildings involves consideration of their long-term adaptability and future use. Designing systems and constructing for flexibility, reconfiguration, and expansion to accommodate changing needs over time. On a material level, rethinking the shift towards sustainable materials, bio-based materials or low-impact ones are to be considered. The industry should also focus on rethinking the functionality of spaces and consider making them multifunctional to optimize space and reduce waste. Lastly, adopting digital technologies by rethinking the significance of traditional methods.

Refuse: Calls for refusing unnecessary material consumption and waste generation through multiple avenues like designing out waste during the design phase itself, reuse, sharing of assets, and switching to virtual services and platforms among others.

Reduce: Focuses on minimizing resource consumption, energy consumption, and material waste by prolonging the life of an asset, increasing efficiency through maintenance, smart technology for tracking and monitoring, and optimizing processes.

Reuse: Promotes reuse of products, materials, and assets within internal loops by designing for durability and predictive maintenance such that they retain their value for an extended lifespan but also reuse through resale and redistribution through secondary materials. This opens new revenue streams in the supply chain.

Repair: Emphasis on repairability on products and calls for maintenance to prolong the life of an asset and reduce the need for replacements.

Refurbish: Advocates for upgrading products or assets to perform the function they are designed for. It elongates their use and reduces material consumption.

Remanufacture: Involves disassembly and rebuilding products to their original or renewed state by also making use of recycled materials during the manufacturing process.

Repurpose: Materials, products, or assets perform a different function or are applied in a different process to prevent them from being dumped.

Recycle: It transforms waste into other resources that can be introduced as materials for other processes, manufacturing, or applications. This transformation is, however, possible only through diligent collection, sorting of materials, and processing.

Recover: Focuses on recovery of energy or other resources from waste that are unrecyclable and avoid being dumped in landfills.

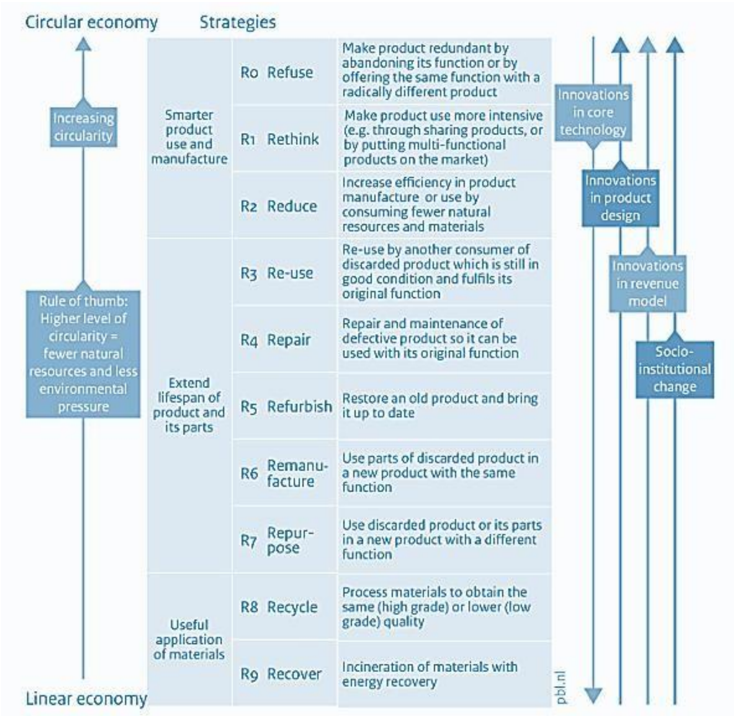

Figure 10: 10R Model of CE (PBL, 2017)

3.1.6.2 Loops for Circularity

This concept encapsulates the four CE resource loops namely, narrow, slow, close, and regenerate. The researcher aims to elucidate the details governing each principle to aid the identification of circular strategies that can be applied to HVAC systems in buildings.

The **"narrowing"** resource loop refers to using fewer inputs in terms of energy, materials, and other resources for the manufacture and consumption of products or even buildings (Bocken N. M., 2016). In the context of the built environment, narrowing indicates the use of fewer resources throughout the building's lifetime (Çetin S, 2021). It is vital to incorporate this principle in the early design phase considering the impact design decisions have on the performance and operation of the buildings in later stages (Kedir, 2021).

"Slowing" resource loops advocate a slowdown in the flow of resources by intensifying their use and extending their service life through design and operation measures (Bocken N. M., 2016) (Çetin S, 2021).

The **"closing"** resource loop intends to reintroduce the resources back into the economic cycle when buildings reach the end of their service life (Çetin S, 2021).

Finally, **"regenerate"** aims to collaborate with local communities and utilize healthy and renewable resources to create a positive impact for both humanity and nature. It requires a paradigm shift from doing things to nature to being a part of it (Reed, 2007). This principle requires a step beyond just green and sustainable building concepts and creates a continuous flow of resources that are self-sufficient (Çetin S, 2021) (Attica, 2018).

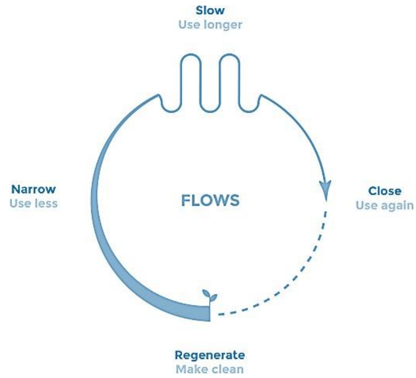

Figure 11: Material and energy flows (Bocken N. K., 2020)

With a strong theoretical foundation of the key principles involved within the concept of CE, the researcher aims to identify circular strategies that can be clustered under these models/principles. These strategies would make for a comprehensive list and have been discussed extensively in the chapter, 5. Conceptual Model. The list would comprise actionable strategies that have practical applications and require implementation not only on a system level but also for the entire building. For instance, strategies like using prefabricated equipment and centralized systems that are intended to narrow the resource loop impact the components and the system whereas passive design influences the entire building. However, it is important to note that, while these strategies and their corresponding application are a comprehensive representation of circularity principles, there are numerous other possibilities to apply them.

3.7 Frameworks and Indicators for Carbon

The circular economy minimizes the need for new materials and maximizes the reuse of resources. This implies a reduction in embodied carbon. However, sometimes, there is a risk of lower efficiency that translates into higher energy consumption and emissions if components/products are reused. Although that can be mitigated by designing for reuse and proper maintenance, it is *crucial to optimize between the minimization of embodied carbon and the minimization of operational carbon emissions.* (Tarja Häkkinen, 2015) Fortunately, there are several indicators and frameworks to assess the carbon footprint which have been mentioned below.

3.7.1 Whole Life Carbon Assessment

It is a methodology that assesses carbon emissions with a building throughout its life cycle (GBC, n.d). The Royal Institution of Charter Surveyors (RICS) methodology is recommended for undertaking detailed carbon assessments (RICS, 2017). This assessment helps architects and engineers understand and minimize the carbon emissions associated with their design over the entire life cycle.

3.7.2 Embodied Carbon in Construction Calculator

It is a tool that enables architects and engineers to calculate embodied carbon emissions from building materials (Cameron, 2020). It allows benchmarking, assessment, and reduction in embodied carbon that is focused on the upfront supply chain emissions of materials. It uses building material quantities from construction estimates or Environmental Product Declarations. They can be instrumental in the specification and procurement of low-carbon options (Transparency, n.d.).

3.7.3 Material Circularity Indicator (MCI) and Environmental Cost Indicator (ECI)

It is a tool that measures the circularity of materials in a product or building that can be used to identify opportunities for improvement. ECI measures the environmental impact of a building (insideinside, n.d.).

3.2 HVAC Systems

Now that there is an elaborate understanding of the principles of CE and the means to implement them, this sub-section will aim to identify the various components frequently integrated in HVAC systems, factors affecting their selection, evaluation criteria influencing decisions, and analysis of current circularity practices. Doing an in-depth study of the systems and equipment used is essential to recommend circular interventions.

3.2.1 Objectives of HVAC Systems

HVAC systems are a key component of the building services layer. HVAC stands for Heating, Ventilation, and Air Conditioning. They are pivotal in offering conditioned air for work process function, occupancy comfort, and good indoor air quality while keeping system costs and energy requirements to a minimum (Sugarman, 2020). ASHRAE established standards indicating that indoor comfort conditions are thermally acceptable to 80% or more of the building's occupants (ASHRAE F. , 2009).

Simplistically, the process involves drawing outside air, heating, or cooling it, and then distributing it to occupied spaces. (Seyam, 2018).

The objectives of an HVAC System in any building have been listed below:

- **Indoor Air Quality**: Circulating clean, filtered, and pollutant-free air for a healthy indoor environment and ensuring optimum comfort through regulated humidity and air velocity.
- **Thermal Comfort**: Providing a desirable state of mind by maintaining appropriate temperatures, crucial for productivity and well-being. Studies show that productivity in an office grew manifold due to satisfaction with the thermal environment and that extreme cases of sick building syndrome were observed due to thermal discomfort. The relevance of thermal comfort for occupants warrants careful design, maintenance, and operation of HVAC systems and is one of the main goals of architects, designers, and HVAC engineers (Chow, 2022). With the advent of climate change, the issue of developing a sustainable HVAC system is even more pressing.
- **Controlling Energy Consumption**: A typical system makes for approximately 40% of the total building consumption (HESS, 2013). HVAC systems represent between 40-60% of energy consumption in Europe. This is further catapulted by the rising trend of energy consumption for climate control purposes (Mugnier, 2015) Hence, integrating energy efficiency is a primary goal.
- **Maintain Proper Airflow**: Maintaining even distribution of humidity and temperature to prevent the growth of contaminants. If airflow is obstructed, it could strain other equipment, reduce lifespan, drive up operating costs, and compromise comfort.
- **Safety**: HVAC systems are essential to prevent the build-up of toxic gases like carbon monoxide and ensure safe working conditions through efficient ventilation and safety features like pressure relief valves

3.2.2 Selection of an HVAC System

Buildings and their corresponding HVAC systems are now required to be both energy efficient and perform effectively concerning their financial and environmental impact (Neto, 2008). The energy performance of an HVAC system depends not only on its configuration and operational parameters but also on the characteristics of the heating and cooling demand of the building (Korolija, 2011)

The factors mentioned below apply to the selection of an ideal HVAC system(s) for any building program regardless of the building type. The selection of a system requires careful analysis of diverse options such that the project goals are met, and optimum performance is delivered (ASHRAE F , 2009). In context with the purpose of this research, knowledge of factors affecting selection can highlight areas where circular practices can align with the needs of the building, and its occupants and propose solutions that are relevant and practical to apply.

- **Building Configuration:** The building layout, room sizes, and ceiling height impact HVAC selection. High-ceiling buildings need air distribution at greater heights. The insulation levels of the building also determine system choice; poor insulation requires a larger system. Doors and windows play a role too. Large, single-glazed windows absorb more heat in summer and lose heat in winter. HVAC systems, their distribution, and other fixings influence architectural design due to their visibility in occupied spaces. Lastly, building orientation also plays a definitive role in system selection.
- **Building Usage:** The nature and level of occupancy affect selection. More people imply a higher demand that can be met by a powerful system. Kitchens or restaurants produce heat and humidity from cooking whereas special equipment in data centers, or manufacturing units requires strict humidity and temperature control. This influences the choice of HVAC systems. Operating hours are also influential. 24/7 establishments need efficient and cost-effective systems. Hospitals need sterile environments, while museums need humidity control for artifact protection.
- **Climate and Location:** Buildings in tropical regions need systems to remove excess moisture and maintain air quality. Extreme temperature changes require resilient mechanisms. Higher-altitude buildings need systems for lower air pressure. Polluted areas require solutions to remove pollutants for a healthy environment. High winds and heavy snowfall also influence HVAC choices.
- **Building Codes/Standards:** The Building Decree 2012 contains the technical regulations that represent the minimum requirement for all structures in the Netherlands and relate to health, safety, usability, and energy efficiency. There are local building by-laws as well which are established by municipal bodies and need to be adhered to and can differ from one municipality to another. For businesses, all new buildings must also now comply with the almost energy-neutral building requirements (BENG) to reduce energy consumption and are different for different building types. (Agency N. E., 2017)
- **Owner's Choice:** The system's selection is driven by the owner's financial and functional goals and project requirements, and the system selected must meet the performance requirements set by the owner (ASHRAE, 2016).
- **Energy Efficiency:** Higher efficiency ratings consume less energy and reduce the operating expenditure over time.It is imperative to choose the appropriate size of the system. Proper design and installation of the system for effective distribution of air is pivotal for efficient operation and performance. Moreover, energy efficiency is enhanced with proper zoning of the HVAC system. It allows selective temperature control in different areas of the building as opposed to the entire building. Regular maintenance is significant for energy efficiency. Periodic replacement of the air filters, replacement of ductwork, and other inspections is essential.
- **Maintenance Requirements:** Complex components like variable refrigerant flow systems could incur more maintenance costs and specialized technicians for service. Systems with regular

maintenance including filter and coil changes could accrue more costs over time. Also, the equipment lifespan can impact operating costs. Longer lifespans imply lower replacement costs over time. Lastly, energy-efficient systems consume less energy and have lower operating costs.

- **Budget**
  - Upfront costs: They can significantly impact the budget. Advanced and energy-efficient systems might have higher upfront costs. In the long run, the initial costs of HVAC systems contribute 20-50% of the total life cycle costs (A. Avgelis, 2009).
  - Installation costs: Complex installation elements like ductless mini-split features may have higher installation costs.
  - Operating costs: energy efficient systems have lower operating costs over time and consume less energy.
  - Maintenance costs: As mentioned above, these costs are periodic and subject to change based on the complexities of the installed system and are perpetual throughout the life cycle of the system.
- **Noise**: Noisy systems can impact productivity and comfort, especially in hospitals, offices, and conference rooms. Careful design and installation of ductwork are required to keep noise to a minimum. Sound insulation can also be added to reduce noise levels.

3.2.3 What is the Process of HVAC System Deployment?

This section aims to delve into the current process of how HVAC systems are installed in buildings. Deciphering the course of action taken across the entire process will reveal prevailing industry practices and the potential to integrate circularity measures. The integration could include considerations for design, material selection, installation, operation, and end-of-life scenarios.

Given below is the entire process with a description of what each stage entails. However, it is important to note, that this is a simplified representation and not a rigid plan followed throughout the industry considering the uniqueness of each project. There are unique stakeholders, project characteristics, specific requirements, and varying contextual considerations influencing the nuances of the process (ASHRAE, 2016).

To arrive at the process, an exploratory interview was conducted with an MEP consultant who walked through the steps taken right from where they first met with the client to the end-of-life considerations made for HVAC systems.

1. Development of Program of Requirements

Typically, the building owner/client approaches an MEP consultant with a document comprising information about the site location, functionality, orientation, and the space plan of the building. Often, the client already has the design team ready with stakeholders like the architect, consultants, owner’s representative, developer, etc. The client’s brief serves as a critical foundation for circularity in HVAC systems as decisions made here determine what considerations can be made during design.

2. Concept Phase

The MEP advisers design a broad idea to meet the building's climatic requirements based on the client and team's ambition and program of requirements. Decisions during this phase may need space plan revisions to accommodate the systems. The best HVAC system is chosen after assessing the construction site for orientation, sun exposure, space, owner's requirements, etc.

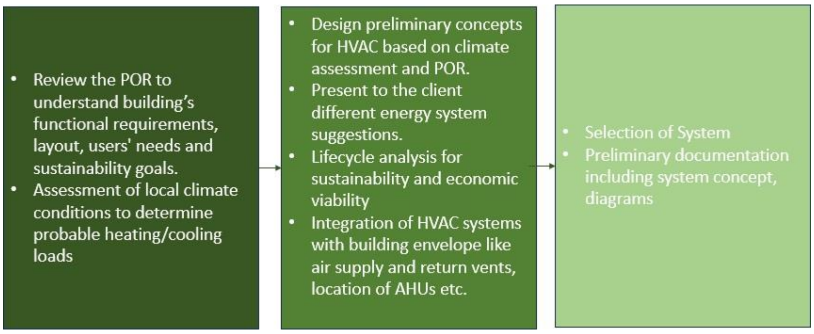

Figure 12: Concept Phase, own figure

3. Preliminary Design

A more extensive analysis is performed for selecting HVAC equipment and components based on energy efficiency, space availability, and conformity with the basic concept. The layout of heating, cooling, and air distribution systems and control systems to manage and optimize HVAC equipment are based on building demand.

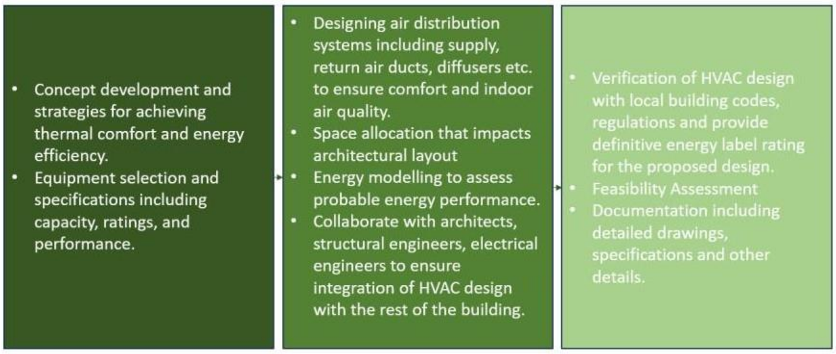

Figure 13:Preliminary Design, own figure

4. Definitive Design

This stage involves the translation of concepts developed until the preliminary phase into detailed technical plans and specifications. The equipment sizing, specific equipment selection, detailed ductwork, and piping are all developed along with a precise control system for optimizing the system's performance. This process entails the preparation of detailed drawings, specifications, and construction documents and serves as the basis for construction and installation.

5. Procurement

Once the detailed design or the preliminary design is complete, the procurement phase involves sourcing and purchasing HVAC equipment and materials as stipulated in the specifications.

6. Construction and Installation

Skilled contractors and installation companies implement the HVAC design according to the approved plan and specifications. After installation, the HVAC system is thoroughly tested to ensure it meets the performance requirements.

7. Use and Maintenance

The completed system is handed over to the users or facility management. Regular maintenance is conducted to ensure energy efficiency and optimum performance. Old and worn-out parts are replaced.

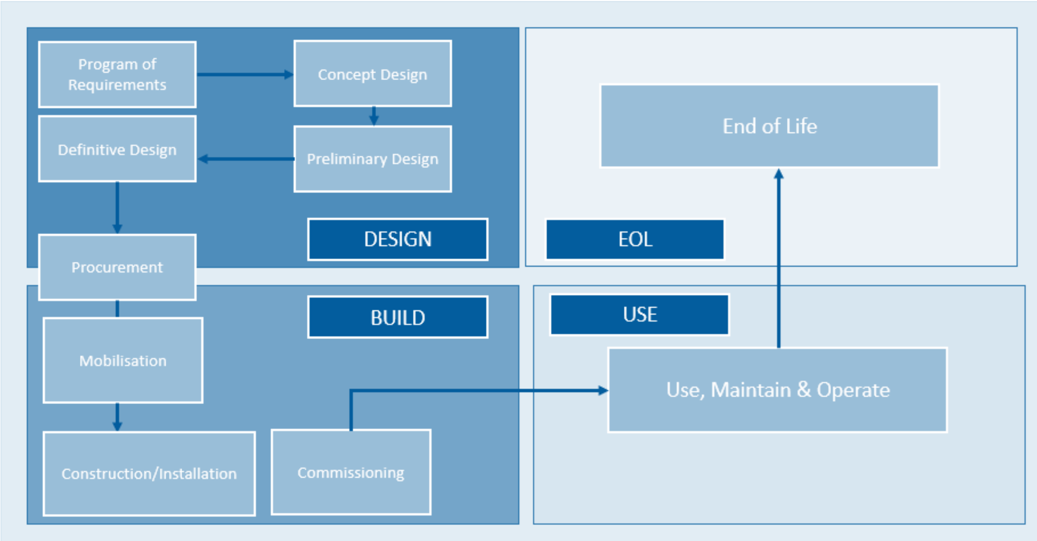

Figure 14: Lifecycle process for HVAC systems, own figure

3.2.4 Current HVAC Systems

This section provides a thorough review of the systems and equipment used in HVAC installations for buildings, establishing the groundwork for a more in-depth investigation of how circular thinking might be applied to improve the performance and sustainability of HVAC systems. Understanding the complexities, composition, lifespan, maintainability, and installation of conventional HVAC systems allows us to spot areas where circular practices can be implemented to reduce waste, increase energy efficiency, and help design more robust and ecologically friendly structures.

3.2.4.1 Heating Systems

Heat generating, distribution, and space heating equipment are the several types of heating system components.

3.2.4.1.1 Heat Generation

1. Boilers

Boilers heat spaces by passing hot water through radiators or other devices. The boiler then reheats the cooled water. They use natural gas, oil, or electricity. Thermostats, valves, and pumps circulate hot water in a boiler. Cast iron, steel, or copper make boilers (House S., 2015). Cast iron boilers cost more but survive longer than steel or copper boilers. Copper boilers are the weakest and almost obsolete in modern boiler systems.

2. Heat Pumps

Heat pumps use the refrigeration cycle to heat by condensing and expanding a gas. Some heat pumps can heat and cool the structure. Unlike heat pumps, chillers remove heat from the building, but less efficiently. Heat pumps move 2–5 times more heat than electricity. However, in outdoor temperatures below 5°C, boilers may work better.

Air-source heat pumps are cost-effective and easier to install compared to ground-source heat pumps. (House S. , 2015). ***Ground source heat pumps***, utilize the stable temperature of the ground, and are more efficient and durable, lasting up to 25 years. Nevertheless, they require complex installation involving digging and plumbing, which can be costly, especially for utility buildings requiring numerous wells. (Venturewell, n.d.). Due to water's conductivity and heat capacity, ***water-source heat pumps*** function better. Adopting this approach requires consideration of availability and environmental impact. (Avelar, 2020)

Heat pumps have a refrigerant, condenser, expansion valve, evaporator, and compressor. Their construction uses steel, aluminum, copper, polypropylene, and polyethylene. HFCs, HCFCs, CO_2, and ammonia can be used as refrigerants. Foam or fiberglass insulation saves electricity and heat. (IM, 2022). The electricity's fuel mix determines heat pumps' carbon impact.

4. Combined Heat and Power plants

They supply electricity and heat. Fuel or fuel mixes power a furnace or gas turbine to generate electricity, and the waste heat heats space or hot water. Renewables may also be used for heat. (Dincer, 2021). This system needs a prime mover like gas or steam turbines, a generator, a heat recovery system to catch waste heat, a fuel system for energy, and a control system for efficient and safe operation. Copper, steel, aluminum, biogas, natural gas, fiberglass or foam insulation, and heat exchangers are the main components. Well-designed and maintained CHPs endure 30–40 years. Maintenance, monitoring, and repair can extend life. However, environmental temperatures, energy demand, fuel quality, and other factors might impact system performance.

5. Fuel Cells

Fuel cells generate clean, efficient electricity from hydrogen or other sources. They can power commercial buildings and long-term grid storage using a variety of fuels. Hydrogen cells emit water, eliminating carbon emissions (EERE, n.d.). They don't emit carbon monoxide or fine dust; thus, their exhaust gases can nourish building green spaces. Fuel cells generate electricity and heat simultaneously. It runs on natural gas because pure hydrogen operation is not yet possible. Hydrogen can be electrolyzed from extra photovoltaic electricity and stored for winter with proper precautions. Biogas might also supply 100% renewable energy. Technology's experimental character makes economic benefits assessment harder (Jurkait, 2019).

6. Solar Thermal

They work better in sunny chilly climates than cloudy or dark ones. Solar radiation heats fluid for space or water heating. Solar thermal systems have a collector, heat transfer fluid, storage tank, and distribution system.

Copper, aluminum, or stainless-steel absorber plates make up the solar collector. Collector glazing could be glass or plastic treated with titanium oxide, black nickel, or black chrome to resist weathering. Water, propylene glycol, or ethylene glycol are good heat transfer fluids, stable and system compatible. Storage tanks might be steel, stainless steel, or glass-lined steel. Finally, pipes and fittings are made of copper, plastic, or stainless steel, and insulation is wool, fiberglass, or foam. A well-designed and maintained system can last 20–30 years or more. System components have variable lifespans. (Jurkait, 2019).

7. District Heating

Buildings can employ district or local heating networks if the heat source is evaluated. Only renewable heat sources can make this alternative renewable. A district heating system has a low-temperature heat source, heat generation, distribution, delivery, thermal storage, and control system. Heat pumps, as already discussed, produce heat. Air, soil, and groundwater can provide low-temperature heat for heat pumps, depending on availability and temperature. Heat is transferred by piping, substations, pumps, valves, and water at the desired temperature or using a common heat exchanger for buildings with smaller heat pumps. (Peeters, 2019).

3.2.4.1.2 Heat/Cooling Distribution

1. Piping

HVAC piping transports hot, cool, refrigerant, condensate, steam, and gas to and from HVAC components. Copper and steel are usually used for piping. Metal pipes cost more than plastic but have a longer lifespan. They also recycle well. Copper pipes are not suited for conveying low-pH water (Kupferinstitut, 2001). Thus, tinned copper pipes exist. Steel pipes are welded, screwed, or flanged, whereas copper pipes are soldered (Adarsh, 2021).

HVAC often uses plastic piping, which is cheaper than metal. They're underground-safe and corrosion-free. PVC and CPVC are popular. PVC pipes are chemical- and corrosion-resistant but brittle. They're unsuitable for hot water. CPVC pipes can handle hot water and high temperatures.

2. Pipe insulation

Insulation enhances occupant comfort by supplying fluid or air at the desired temperature without cost and lowering energy usage by preventing heat loss (or gain). Selecting insulation for an HVAC system requires careful consideration of the operating temperature, resistance to moisture and fire, cost, and availability of the material (HVAC-ENG, n.d.).

- Fiberglass: low cost, easy installation, but limited recyclability. Often mixed with resins or chemicals that could release toxic fibers. Applied as sleeves or spray on (difficult to remove).
- Mineral wool: good fiber and moisture resistance, difficult installation, moderate recyclability. Applied as sleeves or rolls with mechanical fasteners or tape.

- Foam glass: High operating temperature, excellent fire and moisture resistance, easy installation, and high recyclability from recycled glass. Applied as sleeves or panels with mechanical fasteners.
- Expanded Polystyrene (EPS): Low cost, not ideal for high temperatures, not widely recyclable, and applied to pipes like foam glass.
- Spray foam: Versatile, easy to install, suitable for hot and cold climates, but made from petroleum-based chemicals and challenging to remove.
- Calcium silicate: good fire and moisture resistance, expensive installation, generally not recyclable. Applied with pre-formed sections and mechanical fasteners.
- Polyurethane (PUR): Easy to install, suitable for humid environments, but coated with PVC that is difficult to recycle and often made from crude oil.
- Rock wool: Excellent fire, thermal, and moisture resistance, recyclable, and made from natural materials. Applied as pre-formed sections.
- Rubber: Often combined with PVC and other compounds, affecting recyclability.

Pipes are normally insulated after **adhesives** are applied. Polymers, resins, or plant-based ingredients make them. Adhesives depend on pipe insulation material, temperature range, and other considerations. It seals air leaks and bonds surfaces. Due to chemicals and energy use, adhesives' environmental impact is especially crucial during manufacture. Recyclability may also be affected by difficult-to-separate adhesives.

3. Pipe Fixings

Pipe clamps are used to support suspended pipes, connect pipes with other assembly components, and transfer loads to structures. They are usually made up of metals like carbon steel, stainless steel, plastic, copper, brass, aluminum, alloy steel, and chrome-plated pipe clamps or mounting elements, etc. (Dey, 2021)

4. Installations

Installations like valves, flaps, and ventilation devices are made up of metals like aluminum or brass and plastics like PE or PVC. The level of recyclability depends on the material composition and assembly of the products. This is at the discretion of the manufacturer and the design of the component.

3.2.4.1.2 Space Heating Equipment

Space heating systems are designed to satisfy the thermal comfort of the occupants. It is imperative to consider the interaction of the heating system with the rest of the building layers (Brand, 1994) (Heikal, 2011).

1. Radiators

Radiators are popular in homes but also schools, hospitals, and other public facilities. New radiators are energy-efficient and attractive. Some models are also built to withstand commercial abuse. Radiators are rust-resistant. Low surface temperature radiators are safe and convenient for schools and hospitals. To maximize performance, choosing the proper size for the room is crucial. (Harvey, 2017). Renewable energy can power highly efficient radiators. They're easy to install and don't need building integration. (Direct, 2021).

To transfer heat quickly, radiator base elements are steel, stainless steel, aluminum, or cast iron. This mixture simplifies aluminum recycling. Its modest weight makes installation easier (Style, 2019). Due to radiator heat and heat resistance, they are covered with acrylic or synthetic resin. They may reduce recycling quality. These coatings use petroleum-based organic solvents. (Umweltbundesamt, 2012)

2. Surface Heating Systems

Underfloor and wall heating systems: They circulate warm water through pipes under the floor or walls. The floor radiates heat from a boiler or heat pump that heats the water. Thermostat controls are integrated. Wet and electric systems are two alternatives. Electric systems heat tubing with electrical resistance, while wet systems use water. They function at lower temperatures, which increases energy efficiency, lowers emissions, and lowers energy consumption. (Jones G. , 2022).

The pipes commonly used are PE-RT and PE-X which have been elucidated before. Sometimes, copper is also used (Jurkait, 2019). The method of embedding the pipes in the floor or the wall might affect dismantling or maintenance works. The wet systems require a layer of screed to embed the piping distribution. However, it is often powered by heat pumps that make it energy efficient as opposed to electric systems that might be affected by fluctuating energy tariffs (Warmup, 2019).

Ceiling heating systems: Ceiling heating heats the entire surface. For thermal comfort and economy, combined ceiling and wall heating is ideal. In offices, schools, and hospitals, it reduces noise.
It works under plaster and drywall. In drywall, fiberboards with heating pipes are screwed to the ceiling substructure, usually wood or metal. Disassembling is simple. Aluminum composite pipes are rail-mounted to the ceiling. Like underfloor heating, this system features wet and electric versions. Heat pumps power water systems, which use less energy and cost less than electric systems. (Variotherm, n.d.). Disassembling plastered or concrete-encased pipes may be challenging. Thermal stratification reduces efficiency and comfort in this system. Pipes are welded or clamped to steel ceiling radiant panels. Radiator materials cover the panels. (Jurkait, 2019).
Cavity ceiling heating systems between the structural ceiling and the suspended (false) ceiling are easier to maintain and remove. Its metal foundation is coated with paints and other alloys like radiators. (Albers, 2015)

3. Infrared Heaters

They are electrically operated and can be powered by renewable sources of energy. They are easy to install and are made of ceramic or other materials as well. They contain infrared light bulbs, a heat exchanger that has good thermal conductivity like copper, and a fan to create heat by blowing air onto the exchanger. They do not release harmful gases into the air or contribute to emissions (Jackson, 2021).

3.2.4.2 Ventilation systems

Well-maintained, energy-efficient ventilation systems improve indoor air quality and reduce infections. It regulates temperature, humidity, and carbon dioxide, affecting well-being. This was especially true during the COVID-19 pandemic.

Ventilation systems control outdoor air supply, temperature, humidity, and filtration. When constructing a ventilation system, consider occupants' acoustic and thermal comfort. This project is interdisciplinary because furniture, construction materials, finishes, internal layouts, and the envelope affect indoor air quality. (Jurkait, 2019).

The different components that constitute a ventilation system to serve the purpose of mechanical ventilation, filtration, distribution, and control have been elaborated below.

1. Air-handling units (AHUs)

AHUs are large metallic boxes that consist of several other components like blowers, filters, sound attenuators, and cooling or heating coils. They are installed on the inside or outside of the building and come in different sizes with a range of variants. AHUs for multi-unit buildings are much larger and are known as *makeup air units*. The components are usually sourced from other suppliers and assembled to form the entire unit. The housing or casing of the unit is typically made from metal. It also comes with coatings on radiators and thermal insulation that have been elaborated on in the previous sections.

2. Fans

There are three types of fans commonly used in mechanical ventilation (Ali, 2023):

A propeller fan mainly contains impellers, an electric motor, and a casing with fixing points. They cannot handle a large volume of air and operate at about 50% efficiency. They are inexpensive to install and can remove a large volume of air. **Centrifugal fans** comprise impeller blades, an electric motor, a casing, a pulley, and an inlet and outlet. These fans are suitable for long ducted ventilation systems and their efficiency ranges between 45-85%. However, it is bulky which might make installation difficult. Finally, an **axial fan** consists of impellers, a duct flange, an electric motor, and a cylindrical casing. These fans can develop pressure higher than centrifugal fans and are easier to install. It is usually fitted inside the ductwork of the ventilation of air conditioning systems.

Fan blades can be made up of aluminum, fiberglass, marine-grade aluminum, steel, or other composite metals (Immell, 2005). Mixed materials could affect recyclability. Paints, coatings, and other alloys can also affect the quality of the recyclate and energy required for downcycling.

3. Heating and cooling coils

Generally, heating is offered by heating coils in the central ventilation units. They are heated using water, refrigerant, or electricity. They come in the form of tubes, and fins made up of copper, aluminum, and stainless steel and might have layers of paints and coatings. The material composition does depend on the design and the purpose of the coil. The tubes are attached to the fins through soldering, joints, or screws. The tubes and fins might be composed of the same material or have a different makeup (Jurkait, 2019).

4. Humidifiers (Rotasystem, n.d.)

Humidifiers work by circulating spray, steam creation, ultrasonic dispersion, or cold evaporation. Depending on utility building needs, each method has pros and limitations. Utility building humidifiers use stainless steel, ceramic, glass, and plastics. Material selection ensures durability, hygiene, corrosion resistance, and contamination resistance. Ultrasonic humidifiers last around a year, but single-substance or cold evaporator humidifiers last longer. Proper operation and maintenance improve longevity. Humidifier capacity and design affect space requirements. Cold evaporators and some single-substance humidifiers are compact and modular, allowing for space-efficient installation. Humidifier efficiency depends on energy usage, performance, and indoor air quality. Closed humidifiers, like single-substance humidifiers, are more efficient and hygienic.

5. Filters

The frame of most filters is metal, plastic, or fiberboard, and other coatings encapsulate the filter material that removes pollutants, allergies, and other impurities. They usually have natural and synthetic fibers. An air filter's end-of-life contamination makes it dangerous and harmful to recycle (Mint, 2021). Frequent replacement of air filters is one of the primary ways to control and reduce energy consumption. However, this results in a lot of waste. Moreover, when these air filters are dumped in landfills, they are responsible for harmful greenhouse gases and carbon dioxide (Reitmeier, 2016). A few commonly used air filters have been described below (Homeclimates, n.d.):

HEPA filters are cost-effective, efficient air purifiers that cannot filter vapors, smells, or gases. Mold may require replacing sooner. *UV filters* kill bacteria but produce harmful ozone and screen dust and pollutants poorly. They are expensive and require an annual replacement. *Electrostatic Filters* are reusable, anti-allergen, and cost-effective. *Washable filters* are expensive but long-lasting. They are reusable; however, mold prevention requires frequent maintenance. *Media filters* are low maintenance but need to be replaced once or twice a year. *Spun Glass Filters* are affordable and disposable and protect air conditioners and furnaces from debris but need to be replaced regularly to improve indoor air quality.

6. Attenuators

They are used to lower the sounds generated by an HVAC system. They all have similar material composition and construction processes. The frame is made of galvanized steel sheets or aluminum and mineral wool is primarily being used as the absorbent. Other materials include duct sealant, adhesives, and polyester films (Melo-Mora, 2022). Flanges, “Mex”, and spigots are used to build attenuators. (Noico, n.d.). The use of connections like Mez (“slip connection”) can make the installation and disassembly of attenuators and ducting systems easier. Adhesive sprays and petroleum-based plastic sheets can make end-of-life dismantling problematic.

7. Ducts (Panels, 2020)

Rigid Ductwork is trustworthy, durable, and insulated. *Sheet metal ducts* are usually galvanized steel or aluminum. Both are mold-proof and recyclable. *Sheet metal ducts with fiberglass lining* degrade and release toxic fiberglass particles. It's hard to clean and damages the liner, contaminating it. Recyclability may be hindered by contamination and material composition. Fiberglass strands are bonded with resin and foil lamination to protect *fiberboard ducts* from moisture. They are well-insulated yet can grow mold and mildew in humid situations. Heterogeneity and probable toxicity endanger recyclate quality and energy required for recycling. The ductwork system is usually connected using rivets, frames, and bolts. Once the ductwork is fixed, it is sealed using tape, sealant, or a combination (Ductstore, n.d.). These sections can be taken apart and are relatively easier to dismantle. **Flexible Ducts** are typically tube-shaped and made of wired steel coil covered with bendable, durable plastic or aluminum which is further insulated. It is quite easy to install and costs less than rigid ductwork. However, they have specific installation requirements. Seam connections are preferred in the case of flexible ductwork systems.

8. Thermal Insulation

Thermal insulation peculiar to ductwork and AHUs will be touched upon in this section. External insulation prevents condensation and energy loss. It is also sprayed inside to reduce noise, notably in AHUs. (Zhen, n.d.). *Fiberglass insulation with aluminum foil* is most common for flexible ducts. Aluminum foil binds the substance. *Cross-linked polyethylene insulation foam* is ideal for exposed air conditioning and exhaust ventilation ducts. Fiberglass is cheaper. They look better and work safer. *Rockwool insulation with a perforated metal sheet* is used for sound insulation and is preferable to fiberglass because it doesn't tear readily in severe winds. Aluminum foil and sheets may reduce recycling. *Rubber insulation* contains flame retardants and other chemicals that make recycling difficult. Glue makes recycling the built-in rubber installation harder.

9. Variable Air Volume (VAV) boxes

VAV systems use varying airflow at a constant temperature to heat and cool buildings. They reduce energy consumption, offer precise temperature control, and reduce the wear of compressors. They typically contain a damper, a controller, and a coil for heating/cooling that is powered by electricity or water pumps (KMC, 2018). Much like an AHU, the casing of the box is galvanized steel or aluminum and can be disassembled. It does not necessarily have paints or coatings but is relative to the manufacturer (Shavers, 2022).

10. Fire Dampers

Fire dampers represent passive fire protection that is designed to use compartmentalization to prevent the spread of toxic gases, smoke, and fire. A damper consists of a galvanized sheet metal casing, and damper blades made of non-asbestos calcium silicate board. It comes with a sealant made of polyurethane foam and other plastic sealants for ducts. Connections are made through soldering (Systemair, 2023).

11. Supports and fixings

Duct supports and fixings are made of metal and might be covered with thermoplastic elements for anti-vibration characteristics. Galvanized sheet metal is used to make hangers, frames, rivets, and screws. They can be recycled and taken apart as well.

12. Grilles and diffusers

To maintain indoor temperature, grilles, and diffusers are fitted at the ductwork system's terminal point. Grilles have rigid frames with vertical or horizontal vanes. Ceiling diffusers are prevalent. They are built of aluminum or steel and coated with paint or thermoplastic powder (PE, PA, PUR) which have already been described. Powdered thermoplastic coatings stay longer than paints, which can be recycled. It is vital to consider the trade-offs when choosing a surface treatment for these items. Untreated stainless-steel grille/diffusers will last less and corrode. (Jurkait, 2019).

3.2.4.3 Cooling Systems

Cooling systems must also be designed to provide a healthy indoor climate and optimize energy consumption. A healthy indoor climate is influenced by not only cooling systems but also ventilation, heating systems, façade design, interiors, layout, and orientation. For instance, cooling consumption can be optimized by considering shading, energy-efficient lighting, glazing, etc. This section deals with the various components commonly used in different functions of cooling systems.

3.2.4.3.1 Refrigeration systems

Refrigeration systems deal with the transfer of heat from a low-temperature level at the heat source to a high-temperature level at the heat sink by using a low-boiling refrigerant. The commonly used refrigeration systems have been discussed below:

1. Compression Chiller

Healthcare facilities, factories, commercial buildings, and office spaces generate unwanted heat that is removed by vapor compression chillers that use a mechanical compressor powered by electricity, steam, or gas turbines. There are air-cooled systems and water-cooled systems each characterized by different features elucidated below (McDonald, 2020). Other components typically found in a vapor compression chiller are a compressor, condenser, expansion valve, and evaporator.

Characteristics	Air-cooled Systems	Water-cooled Systems
Capacity	Lower capacity; higher footprint.	Higher cooling capacity with fewer units and smaller footprint.
Maintenance	No need for cooling towers.	Cooling towers have critical maintenance demands and large supply of makeup water to replace evaporated volume in cooling towers.
Location	Easier to operate even in sever winter conditions. Take up less space due to no cooling towers.	Take up a lot of space and cooling towers may need special control, basin heaters etc in cold conditions.
Energy efficiency	Lower energy efficiency	High energy efficiency; might drop in night-time.
Installation	Most are packed systems. Reduces design and delivery time and simplifies installation.	They have complex system components like cooling towers, control, pumps etc.
Lifespan	15-20 years	20-30 years
Water conservation	Ideal in places with water shortage since it does not require water.	Advantageous if water is reused.
Cost	Less expensive.	More expensive.
Materials	Consumes lesser material.	More material on account of more complex components.

Table 1: Comparison of air-cooled and water-cooled systems (own figure) (Wieman, 2019)

2. Absorption Chillers

They use hot(waste) cooling water to produce chilled water serving the HVAC installations. They only consume a small amount of electricity to run the pumps and can result in energy savings of up to 95%. They generally use steam or hot water to drive the refrigeration process (Hopman, n.d.). This heat can come from renewable sources of energy as well. It consists of seven main components: a generator, condenser, expansion valves, evaporator, absorber, pump, and heat exchanger. Two main fluids flowing through the system are a refrigerant and an absorbent. (Mamdouh, 2021). They are most cost-effective at sites that have significant space conditioning loads including hospitals, hotels, large office buildings, and college campuses. The absorption chiller process is an exothermic reaction, and the heat must be rejected. This might require additional space and material for the equipment to dissipate, process, or store the heat. The emissions depend on the thermal source used to power the process. If it is used in conjunction with CHPs, there are no incremental emissions from it (Energy E. E., 2017).

3. Refrigerants

Refrigerants capture heat and release it to another space using the laws of thermodynamics. However, they have detrimental impacts on the environment especially the depletion of the ozone layer and increase in GHGs. The refrigerants in the market now do not contribute to ozone layer depletion anymore but they are greenhouse gases that can be released if there are leaks. A few natural refrigerants mostly used are ammonia, carbon dioxide, hydrocarbons like isobutane, and propane (Ciconkov, 2018).

3.2.4.3.2 Cooling Release Systems

1. Ventilation

It is the least expensive and most energy-efficient way to cool buildings. Central ventilation can often suffice the cooling needs of a building. Other avenues of ventilation like ceiling fans, window fans, etc. can meet the cooling requirements of an indoor space.

2. Active chilled beam systems

Active chilled beams are used if chilled ceilings/ceiling heating systems cannot handle the cooling demand. Active chilled beams work well in schools, offices, and hospitals. These systems manage return air and a lot of space load, reducing ductwork, size, and capacity of air handler components including heating/cooling coils, filters, fans, etc. This system's flexible architecture can create optimal indoor climate conditions over the building's lifetime despite layout changes (Espinosa, 2013).

It also saves energy. Efficiency and energy savings result from water temperature supply requirements. Finally, chilled beams are simple, reliable, and require minimal part replacement (Espinosa, 2013). Ceiling-mounted brackets or hangers connect chilled beam systems to building structures. They're modular and removable.

4. Fan coils

Comparatively, fan coils are simple. Fan coil units have filters, fans, coils, and heating and cooling sources. Fan coils can be exposed or concealed, horizontal, vertical, or ducted. Since the temperature difference helps comfort, systems with higher chilled water temperatures are best for a healthy indoor climate. Fan coils are built for lower temperatures; thus, they cannot manage heavy cooling loads for optimal comfort and may use more energy. Higher chilled water temperatures require more blowers and other components. (Jurkait, 2019).

5. Split Systems

Split systems use an inside evaporator and an exterior compressor. The cooling circuits contain the cooling medium. No heat exchangers are needed. However, refrigerants are polluting. They function at very low temperatures, requiring more energy to remove heat from the operation. (Jurkait, 2019).

3.2.5 What are the Evaluation Criteria for HVAC Systems?

Studying the diverse HVAC systems employed to meet specific objectives reveals their intricate composition, lifespan, installation, and functionality. Gaining a comprehensive understanding of these existing systems provides valuable insights into potential circular interventions that can be proposed. However, it is imperative to evaluate the impact of these interventions on the HVAC systems. To achieve this, it is essential to identify and consider the evaluation criteria commonly used to assess the current HVAC systems' performance across various factors. These criteria comprehensively gauge the efficiency, effectiveness, and overall performance of HVAC systems. The relative importance of these factors varies with different owners/clients and is also different from one project to another when it is the same owner. Each factor has a different priority, depending on the owner's goals (ASHRAE, 2016). Incorporating sustainability and circularity goals is also contingent on the owner and their ambition. However, MEP consultant can play a pivotal role in developing circular ambitions regarding building installations and together with the design team and other stakeholders choose and design systems that can conform to the owner's goals. Analyzing how the proposed circular interventions compare against these evaluation criteria is vital in understanding their potential influence on current HVAC systems and in devising recommendations for enhancing sustainability and efficiency in HVAC service delivery. Comparing the strategies against the industry standard is a good starting point to help weigh the benefits, drawbacks, and potential risks.

Evaluation criteria used to assess HVAC systems have been identified and listed below:

1. Ventilation is the ability to sustain the indoor air quality of an area and filter the air of elements harmful to human health (Sundell, 2011)
2. Relative Humidity reflects the system's ability to maintain humidity at preferred levels which are not only important for humans, but also specialized environments needed for buildings like museums. (Frias-Martinez, 2005)
3. Noise is an important factor in HVAC system selection, lack of noise reduces stress and discomfort. (Leite, 2009)
4. Thermal comfort, as mentioned before, directly affects health and productivity. (Pinto, 2015)
5. Costs. This criterion has been elaborated upon previously in section 3.2.2.
6. Water consumption is a significant criterion considering HVAC systems consume almost 48% of the total water used for an industry building. (Eades, 2018)
7. Energy consumption It has been elaborated upon previously in section 3.2.2. It is highly correlated to energy efficiency. (Zajic, 2011)
8. Carbon emissions include emissions from consumption but also consider features required to reduce environmental effects. (Al-Waked, 2017)
9. $COP_{heating}$ and $COP_{cooling}$ measure the performance of the system as a ratio of useful heating/cooling provided to work required for the HVAC system (Dincer, 2021).
10. Control zones as single or multiple zones are a measure of the ability to control the air temperature and the influence on personalized thermal comfort. (Afram, 2014)
11. Area requirement is the area required by HVAC equipment within the building and outside of it. It depends on the type, specifications, and additional equipment required for the project. (Wang W. H., 2006)
12. Appearance deals with the aesthetic aspect considering the effect these systems have on the building and the visual quality. (Gang, 2005)
13. Installation flexibility represents the complexity of the system relative to the number of components and complexity in installation. (He, 2009)

14. Integration flexibility evaluates the system's compatibility with other components that are either already installed or would be due to modifications or upgrades.
15. Energy source flexibility evaluates energy availability and accessibility of the systems to these sources. (Aazami, 2011)
16. Ease of maintenance implies the simplicity of the system that requires only general maintenance and can be addressed in a short time. It reduces the risk of unexpected failures and can drive up the frequency of predictive maintenance. (Mossolly, 2009)
17. Lifetime of the equipment is a very important criterion affected by the proximity to pollutants, exposure, frequency, and accuracy of maintenance. (Chinese, 2011)
18. Repair time represents the time required to address planned and unplanned repairs throughout the lifetime. 74 (Wang, 2009)
19. Vendor availability evaluates the availability of the system and its spare parts in the market and includes risks associated with transportation of units to the location of installation. (Arteconi, 2017)

For ease of understanding and comparison, these criteria have been grouped into five main categories and presented in the table below (Bac, 2021).

Ergonomics	Costs	Technical Properties	Physical Properties	Flexibility	Reliability
Ventilation	Upfront	Water consumption	Area Requirement	Installation Flexibility	Lifespan
Relative Humidity	Maintenance	Energy consumption	Appearance	Integration Flexibility	Repair Time
Noise	Operations	Carbon emissions		Energy source Flexibility	Vendor Availability
Thermal Comfort		$COP_{heating}$ and $COP_{cooling}$		Ease of maintenance	
		Control zones			

Figure 15: Performance evaluation criteria for HVAC systems, own figure

3.2.6 Issues prevalent in current HVAC Systems and their Lifecycle Process and potential link with Circularity

An analysis of the current systems reveals their complexity and the number of different materials involved in their composition (Christina Kiamili, 2020). A large contribution of metals in a building can often be contributed to the HVAC industry (Oosting, 2021). However, many LCA studies neglect the embodied impact of HVAC systems even though GHG emissions during manufacturing and maintenance of HVAC Systems account for about 13% of the total emissions of office buildings. (Jakob, et al., 2016).

This establishes the need to reduce the embodied carbon because of HVAC systems and their emissions due to operations. Studies are more focused on increasing the energy efficiency of these systems to reduce their operational carbon, but embodied carbon reduction is yet to gain impetus (Croxford, 2018).

To shed further light on the impact of HVAC systems, a paper concluded, that the mechanical equipment, together with ducts and pipes were the main contributors to the total lifecycle GHG emissions for an office building in Switzerland. While this was case-specific, the paper identified that compared to the existing knowledge for the total embodied impact of office buildings, the HVAC embodied impact was in the range of 15-36%, significantly higher than previous studies and estimations. (Christina Kiamili, 2020)

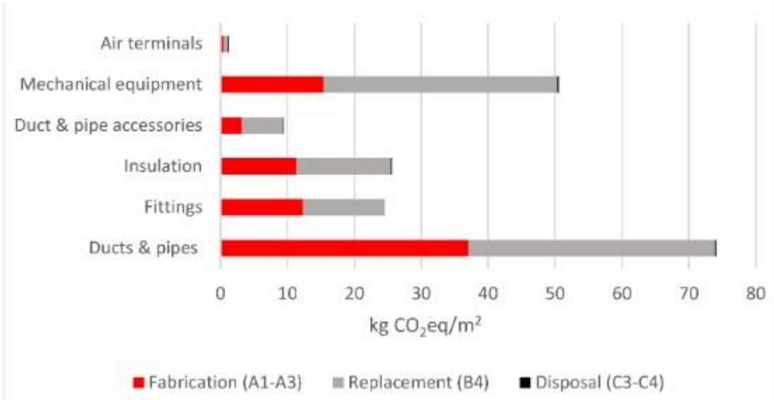

Figure 16: Climate change impact of HVAC systems (Christina Kiamili, 2020)

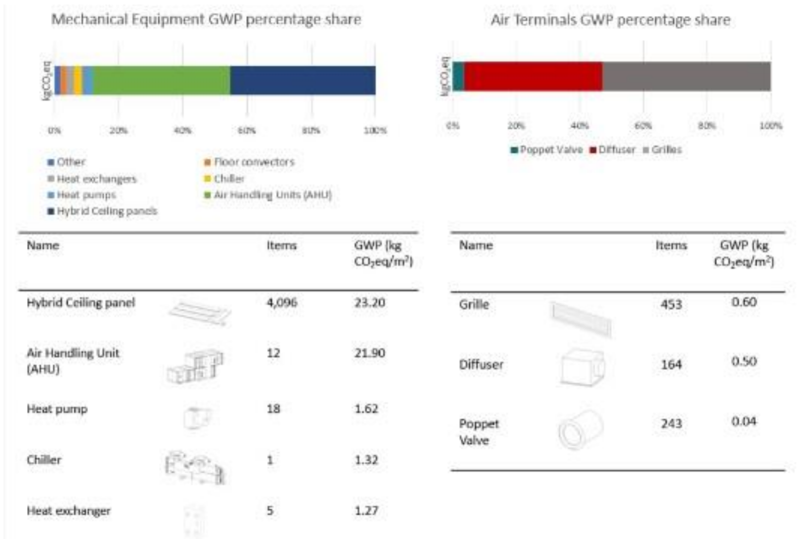

Figure 17: Global Warming Potential of Mechanical Equipment and Air Terminals (Christina Kiamili, 2020)

Also, the use of refrigerants that are often in small quantities end up in landfills and have disastrous consequences if they leak. Also, refrigerant losscan happen during any phase of an HVAC system's lifespan (Wheeler, 2019).

Moving on to the process of designing HVAC systems for buildings, a common source of inefficiency that reduces the sustainability of these systems is over-engineering, often a cumulative effect of different stakeholders adding safety margins to the requirements and specifications to mitigate risks (Bacon, 2014) (CIBSE, 1998). Overdesigning could be driven by many reasons like avoiding risk, redundancy (extra equipment in case one fails), rules of thumb, or flexibility in design (Jones D. A., 2019). However, a significant driver for overdesign is often the number of stakeholders involved in a project who all have different views, potentially leading to conflicting needs (Jones D. E., 2018). Overdesigning equipment does increase the level of embodied carbon. The design process needs to encompass the lifecycle of materials to consider and define future methods of maintenance, disassembly, and reuse of building materials (Kozminska, 2019)

One can infer that despite their quantity compared to other building materials, their environmental impact is significant. However, ways to counteract its effect have been limited. One of the reasons is that in an analysis of the built environment, the impact of building services is often dwarfed by the impact of building materials like concrete which accounts for 10% of the world's energy consumption (Hein, 2021).

This research will focus on the application of identified circular frameworks to develop a solution that can be applied to HVAC installations and other alternatives. This is essential since circular interventions in HVAC installations are limited with limited research done to propagate this transition (Oosting, 2021).

3.2.7 Current Circular HVAC Solutions

Circular interventions in this industry are limited but there are a few pioneers who have set the pace for circular transition. A few initiatives have been identified for this research and have been described below.

1. Pump Solutions

A Danish company has focused on optimizing the manufacturing process and reducing the consumption ofmaterials and energy for the production of pump solutions for HVAC. They have developed a program to takeback pumps from the installers after the end-of-life while replacing them. Moreover, they also offer a service model that provides installation, maintenance, operations, and replacement to make the system more reliable and offer efficient life cycle solutions (Grundfos, 2017) (Croxford, 2018).

2. Airconditioning Solutions

A Singaporean company designs and retains ownership of the air conditioning system with the service offered at no upfront cost but as a monthly fee charged as per use. The company is also responsible for all the operation costs including repair and recovery of components at their end-of-life (Croxford, 2018). Another firm is developing a material passport by amalgamating information about as many recyclable raw materials for reuse later. They are also offering the product-as-as-a-service solution to its customers.

3. Modular Air Handling Units

The company has developed a plug and play concept which allows easy installation, commissioning, and disassembly of an air handling unit and is the sole manufacturer to offer a complete ventilation and coolingsystem. They have developed preconfigured sizes, had standardized components, and focused on reduced energy and operating costs through smart controls (Daikin, 2023).

4. HVAC Air Filters

An organization in the USA has developed a system to solve the problem of air filter waste to prevent it from being disposed of in landfills or dumpsters. It collects clients' air filters, collaborates with a facilitythat produces energy from waste and can produce high-pressure steam that powers a generator that ultimately sends power back to the grid (Reitmeier, 2016).

5. Ducts

Textile-based ducts are being used and developed that are not harmful to human health, have a high recycling rate, and have a long life of up to 25 years with proper maintenance (Jurkait, 2019).

Other solutions have been developed to conform to sustainability and circularity ambitions. These include the use of materials that belong only to the biological cycle, or the technological cycle illustrated in the butterfly diagram (Jurkait, 2019), using waste heat for powering HVAC systems, among others. However, a few examples listed above have been included to offer a glimpse into the current practices being undertaken in the industry. Identification of select circular solutions within the industry serves to showcase their potential and be considered as success stories to inspire stakeholders to explore these alternatives further. They represent only a fraction of what is possible and underscore the feasibility of applying circular principles to other systems and components as well. Subsequent chapters delve into details of possibilities to initiate and implement such circular practices effectively.

4. Stakeholder Analysis

The literature study encapsulated important concepts and practices related to both circular economy and HVAC systems. The previous section aimed to understand the current state of circularity in this segment and explored its potential. This can be further understood by analyzing the various stakeholders involved, which could enable the transition of this industry to become more circular.

This chapter's objective is to identify key stakeholders throughout the HVAC system's lifecycle, comprehend their role, their position in the life cycle, and their influence in a transition towards circularity. This is particularly important due to the construction sector's slow adoption of innovation (BIS, 2013), and the complex, project-specific supply chain (Pomponi, 2017). Moreover, there is a need to decipher the relationships existing among these stakeholders and explore the level of collaboration considering limited practical awareness (Adams, 2017). It is also quite apparent from the literature review that both circular interventions and the lifecycle process of HVAC systems require a multi-disciplinary effort and if new, upcoming concepts are involved, it does necessitate a shift in the way of working.

4.1. MEP Consultancy

Consultancies work closely with the client and with the architects. The association of consultancies with the client, the architect, and the contractor varies according to the contract type and project delivery model. Moreover, there are several kinds of consultancies depending on the expertise they have and the services they offer. The responsibility of a consultancy also depends on the project's requirements and the client's discretion. Since this report is intended to understand the different circular strategies that can be applied to HVAC Systems and their consequences, this study is intended for consultancies who can refer to it to advise their client of the best practices/alternatives for current systems. This is why it is first important to understand their role, responsibilities, and involvement in the lifecycle of the process.

Specific to HVAC systems for buildings, several consultancies depend on the scope of services they offer namely:

4.1.1 MEP Design Consultancy

They create efficient, dependable, and code-compliant MEP Systems (Mechanical, Electrical, and Plumbing) with architects and project owners. Some consultancies specialize in preliminary system design, which involves feasibility studies to determine the economic and technical viability of several MEP design solutions. They also create conceptual system designs that satisfy project goals and cost estimates to help the client make decisions. They collaborate with structural engineers and electrical engineers to ensure the design matches the building's overall design. A few consultancies specialize in extensive MEP system design that includes load calculations to assess building heating and cooling needs. They prepare precise construction documents with technical requirements for contractors to use throughout the building and installation.

4.1.2 MEP Engineering Consultancy

Engineers in an engineering MEP firm give engineering and design services to architects and clients during the design phase. They prioritize project needs energy and performance optimization. Energy modeling, energy consumption prediction, and system performance optimization through rigorous analysis and calculation to select appropriate equipment may also be part of their work. Engineers can model air and fluid flow using Computational Flow Dynamics (CFD) to optimize HVAC system design and air quality. Some consultancies offer commissioning and testing together with engineering and design.

There are **other consultancies** whose specific services might vary but their ultimate purpose is to provide expertise and solutions regarding HVAC system design, optimization, and energy efficiency among others. For instance, the ***Building Physics*** domain specializes in the analysis and optimization of the physical behavior and performance of buildings.

This classification is an overarching representation of most consultancies involved in delivering HVAC system solutions for a project. Some firms might deliver services of design, engineering, construction, and maintenance. The list above encapsulates most of the roles a consultancy might play in the value network. Consultancies also focus on designing sustainable MEP systems by offering environmentally conscious solutions, reducing waste of energy and water, and including energy audits conforming with LEED or BREAM.

4.1.3 Role of MEP Consultants in Circularity Context

Sumter et al recognize the changing roles of consultancies that anticipate future life cycles, and environmental impact, and engage with both external and internal stakeholders to inform of the value of CE and how to proceed towards it. (Sumter, 2018)

MEP consultants also need to develop design approaches that support the flexibility of space and optimize deconstruction to adapt to change. They also need to understand the components and products' material composition whilst designing the HVAC system to meet the project's requirements. Product selections in terms of embodied carbon can lead to an overall reduction of embodied greenhouse gas emissions.

However, currently, the engagement of consultancies is based on a linear logic wherein design and other services often involve a short-term effort, and engagement between the consultant and client ceases after the design is handed over which limits the potential for circularity. Extended partnerships with clients can enable consultancies to evaluate the entire life cycle of the designed solution and observe how it changes with time (Dokter, 2021).

4.2 Building Owner/Client

A building owner or the client for any project is a key player, especially in the early design phase. Owners and their representatives have the main role in developing a program of requirements. They also seem to play a critical role in defining the building parts along with architects, consultants, and engineers. They are usually responsible for the cost of HVAC installation, maintenance, and operation which explains their objective of ensuring the system is designed to be efficient and cost-effective. The client is also concerned with providing optimum occupant comfort and ensures the HVAC system is designed to deliver on that front. Building owners are becoming increasingly aware of their carbon footprint and energy consumption to increase their building's sustainability quotient whilst meeting all the relevant regulations and standards. Moreover, they are mindful of the life cycle of the system and want to retain as much value throughout and keep operating costs at a minimum.

Clients play a significant role in the adoption of Circular Economy for HVAC systems in buildings. Adoption of circular approaches presents an opportunity for clients to minimize resources of lost value thereby improving their return on investment and improving their emissions target.

4.3 Architects

Architects work closely with the client and translate the program of requirements into a building concept. The role of an architect is not restricted to just design but also includes responsibilities of accounting for functional needs, aesthetic objectives, and sustainability goals. Although architects employed by the client are not key decision-makers, they work very closely with them and significantly influence decision-making. They work closely with the client to conduct site analysis and evaluate factors like topography, environmental conditions, and zoning requirements and are also responsible for preparing detailed construction documentation including plans, and specifications among other duties.

Specific to HVAC systems, architects work with clients to assess their HVAC needs by evaluating factors like occupancy levels, air quality requirements, and efficiency goals. They design the Skin, Structure, Space plan, and even Stuff for buildings that directly affect the choice of HVAC system along with the selection of materials and products.

In the context of circular economy, architects need to develop design approaches that move away from single function mentality and design spaces that conform to flexibility. Designers must modify their style and optimize deconstruction (Kibert, 2003). For instance, Morel reports that a project was designed to avoid hiding structural walls or fully integrating HVAC systems (Morel, 2021). Also, they must ensure the recyclability and reusability of all the products by knowing their composition and understanding the impact of the choice made (Charef R. L., 2021).

However, there are a few issues to this link in the value chain that could hinder circularity in HVAC systems. In the case of small enterprises, they often do not have enough resources to make embodied carbon assessments for material and product selection (Häkkinen, 2015). Moreover, efficient collaboration is necessary between manufacturers, suppliers, and end-of-life parties in closing the material loop and avoiding waste and component toxicity. Architects need to collaborate with other stakeholders to share a vast amount of data from design to completion and adopt an overall view of the system's lifecycle (Fadeyi, 2017)). Their recognition is important for the scope of this study since their work fundamentally influences the need for HVAC systems for a building and helps the consultants design systems and buildings that have reduced consumption of resources for thermal comfort.

4.4 Manufacturers and Suppliers

HVAC manufacturers can design, assemble, and produce components and equipment necessary to create efficient, safe, and reliable HVAC systems for different applications i.e., for residential, commercial, industrial purposes, etc. They can provide equipment ranging from basic thermostats to complex air handling units and heat pumps. The range of equipment depends on the scale of the manufacturer, the complexity of the project, and the purpose of the system among other factors. Some manufacturers offer a one-stop solution for all the equipment needed. However, some have specialization in specific HVAC products.

Manufacturers not only produce the necessary equipment but also offer technical support services, maintenance guidelines and train personnel to carry out installation and maintenance. Some of them also develop tools for automation and control systems to optimize airflow, energy consumption and enhance indoor air quality.

Manufacturers work closely with the HVAC contractors to ensure their products conform to the requirements of the project. Important factors like life cycle cost, maintenance requirement, sales support, and energy labels are considered during the selection of manufacturer. However, the supply chain corresponding to manufacturers is quite complex and fragmented. Often the products and components are sourced from different avenues which affect collaboration and standardization of products. Moreover, there is less information available about material composition which can affect circular initiatives and selection of equipment with lower embodied carbon. Additionally, the use of secondary products and materials is still not conventional. It is unaddressed during the design phase. It is vital to reconsider the ways products are designed and put manufacturers and designers at the core of the circular design process (Charef R. L., 2021). Manufacturers also need to change their current mindset of viewing suppliers as companies providing them with materials but think of them as innovation partners and change traditional vendor-client relationships (Dokter, 2021).

4.5 Contractor

Delving into the stakeholders involved concerning HVAC systems for buildings reveals that an HVAC contractor is central to many interactions and works closely with all the primary stakeholders. The contractor has the most expertise on-site and is responsible for overseeing the physical construction and installations following the design requirements. The contractor possesses a lot of knowledge about materials and is instrumental in determining the ideal manufacturer that can meet the project's requirements. This makes them key actors in influencing decisions related to material selection and can bolster reuse.

The HVAC contractor can actively be a part of circularity initiatives for a building due to their knowledge, but this can only be fostered through their early involvement in the project. Traditional procurement methods allow the appointment of a contractor very late or once the design and detailed specification is defined (Charef R. L., 2021). However, for a CE approach, it is imperative to include them earlier, during the design phase, when decisions about building systems and materials selection are made. If methods like Design for Disassembly are undertaken as a CE approach, it is vital to include the contractor early on since consideration of an asset as an assembly of systems requires a contractor's know-how during design phases (Song, 2009). It calls for increased collaboration, early involvement of stakeholders, and transparency among the networks.

4.6 Facility Manager

Their main role is to oversee and manage the operation, maintenance, and repair of the building's equipment and systems to ensure a safe, healthy, and comfortable environment for the building occupants while also maintaining the building's value over time.

Good collaboration with facility managers throughout the lifecycle of the project and their early involvement can help promote circular principles (Charef R. L., 2021). For instance, during the design phase, they can influence decision-making during the selection of HVAC equipment and systems based on their expertise in maintaining, operating, and repairing systems that also retain value over time.

They can also work with contractors and service providers to identify opportunities for reuse, recycling, and repurposing of components and materials. The use of BIM can enable facility managers to use the data embodied in the interface for maintenance and operation activities and can also help them exchange data with stakeholders like secondary markets for material recovery, reuse, and recycling (Charef R. E., 2019)

4.7 Secondary Market Owners/Urban Mining Companies

This entity acquires previously used systems and components from building owners, equipment dealers, auctions, etc. Once acquired, they may later resell, refurbish, repair the equipment, or even supply it for maintenance. They can play a key role in implementing circularity for HVAC systems since they help prolong the life of the equipment, extend its lifespan, and reduce waste. Again, collaboration is necessary to ensure circular initiatives from their end. Building owners can work with them to meet the project's requirements. Early involvement is crucial, particularly to deliver requirements regarding the design, construction, management, and end-of-life of the asset. The use of BIM can help this stakeholder identify components and relevant information about maintenance and repair. This is crucial to ascertain the reuse quotient of the asset. Information compiled in a material passport can again help them determine the origin, composition, toxicity, and quality of materials.

6.1.2 KEY ROLES & RESPONSIBILITIES OF STAKEHOLDERS discusses findings from interviews conducted with these stakeholders. These insights aligned with existing literature findings while also introducing new observations, which are subsequently discussed. This combined information is crucial for comprehending the potential contribution of various stakeholders in the HVAC industry's transition towards circularity, shedding light on their capacities and roles.

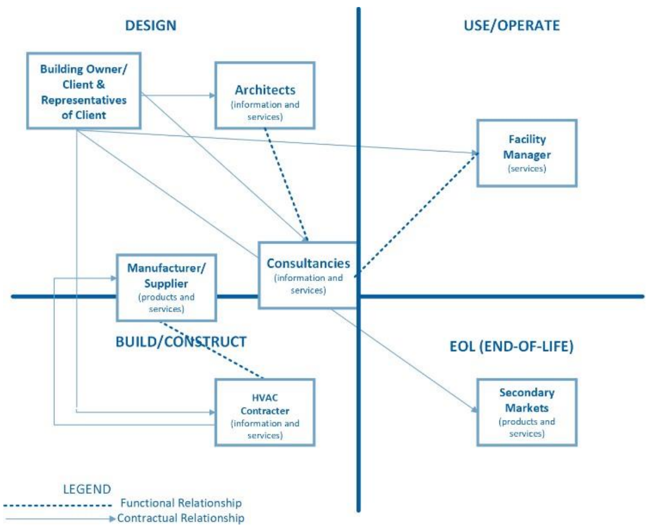

Figure 18: Stakeholder Analysis of HVAC system industry, own figure

5. Conceptual Model

After a careful analysis of the available literature, there is a thorough understanding of the relevant concepts and principles of circular economy that could potentially be adapted for HVAC systems in utility buildings. With the information aggregated during the literature review and stakeholder analysis of the HVAC systems industry for buildings, an approach has been developed for the systematic application of circular principles and their corresponding strategies.

Furthermore, an analysis of the impact of circular principles on the factors affecting the performance of an HVAC system for a building will be conducted. This is essential to determine the feasibility of the implementation of circular economy principles from a practical standpoint and how it compares against conventional HVAC systems. This model aims to establish a link between the proposed circular principles with the factors mentioned in **3.2.5 WHAT ARE THE EVALUATION CRITERIA FOR HVAC SYSTEMS?** to realize the influence exerted on each factor.

The development of the model will be followed by semi-structured interviews with the identified stakeholders from the industry. These interviews aim to elicit information about the barriers and opportunities corresponding to the implementation of the identified principles for HVAC systems and offer insight that can help augment the model. Furthermore, this methodology offers a practical perspective and helps determine the plausibility of the transition of a conceptual model into a real tool that can be exercised in the industry. Insights from these interviews will help tweak the model and help the researcher establish a relationship between the circular strategies applied with the performance evaluation criteria.

To summarize, the circular strategies for HVAC systems aligned with the phases of the project will be introduced in this chapter whereas their influence on HVAC systems will be elaborated upon in **6. DATA ANALYSIS AND RESULTS.** The process followed to arrive at the development of the research deliverable is illustrated below:

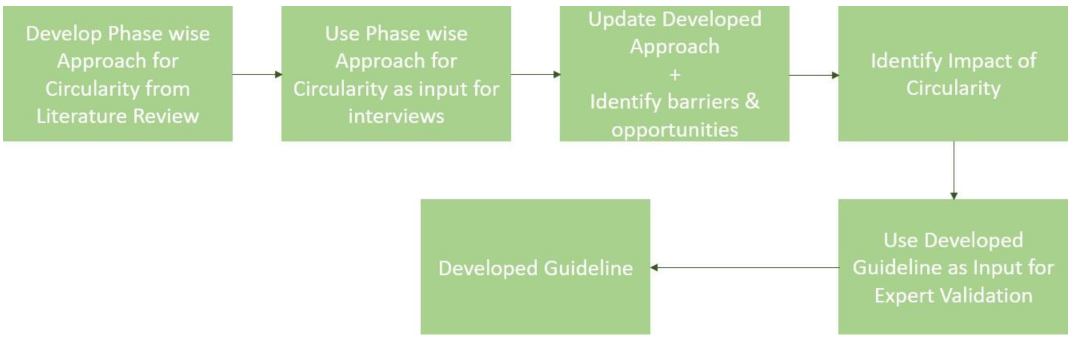

Figure 19: Process for arriving at Developed Guideline

5.1 Phase of the Project

The first element of the model creates structure and offers solutions that can be implemented systematically throughout the lifecycle of the project. CE thinking requires an extended life cycle approach wherein each phase is not only distinct but also part of a continuum. Properly identified stages can enable assigning responsibilities to the relevant stakeholders and analyzing the impact decisions made during these phases have on the circularity quotient throughout the lifecycle of the building. The process described in 3.2.3 What is the Process of HVAC System Deployment? is an existing building lifecycle stage often followed by practitioners. However, it is discovered that it lacks sufficient stages to observe CE principles. It is observed that most processes often start with a feasibility analysis and end-of-life is the final stage. However, from a CE standpoint, a pre-feasibility stage is also necessary to explore options to reduce or eliminate resource usage (Çimen, 2023). Similarly, the final period of the lifecycle can be seen as a Circulation stage as opposed to End-of-life which allows the application of relevant circular principles to circulate resources or products. Therefore, this framework develops a circular building lifecycle from Inception to Circulation where the design process encompasses the lifecycle of the materials- maintenance, disassembly, and reuse. (Çimen, 2023).

5.1.1 Inception

This stage assesses the needs for the proposed endeavor. It involves a consolidated effort to understand the goals of the organization, the objectives of the project, opportunities, and recommending proposals for the same. This culminates in the **brief** of the project. This stage can be utilized to deliberate on the fundamental need for HVAC systems at the get-go of a building's lifecycle. Decisions made in this stage could result in circumventing the need at the earliest point and reducing resource consumption to a minimum. From a CE perspective, including resource efficiency and circularity objectives in addition to time, cost, and quality deliverables is essential and enhances the brief. Furthermore, this stage includes decisions like the functionality, and the location of the building, features that have significant implications on circularity.

5.1.2 Feasibility and Planning

The possibility of meeting the requirements established during the inception stage is analyzed in this phase. An evaluation is conducted to assess the viability of the project against economic, environmental, technical, and social factors. It helps ascertain if the project is worth pursuing and is a vital piece for the decision-making process. Employing the 3.7 Frameworks and Indicators for Carbon can help assess energy consumption, emissions, and resource depletion to identify potential to reduce resource use, and environmental footprint.

5.1.3 Design

Depending on the complexity and scope of a project, this stage might have substages like conceptual design, preliminary design, detailed design, and final design. Decisions made during this phase can have a long-term impact throughout the lifecycle of the project. Several circular interventions could be implemented in this phase and its constituent sub-phases which will be discussed in the next element, **5.2 CIRCULAR STRATEGIES**.

5.1.4 Construction/Build

It is essential to evaluate if the circular strategies designed and developed during the initial stages have been adhered to, according to the design requirements.

5.1.4 Use/Operate

Also known as the facility management stage, it is the longest stage and often has a large impact on the environment. It is pertinent to ensure that the asset is performing as it was designed for and develop predictive and preventative measures to reduce the gap between design and performance.

5.1.5 Circulate

It is also referred to as decommissioning or disposal which has a very linear annotation. From a CE perspective, labeling it as Regenerate or Circulate aligns with the principles of Circular economy which advocates for keeping materials in a loop. Moreover, there are actionable strategies that can be implemented to not only prolong the life of the asset but also ensure the circulation of the material stock.

5.2 Circular Strategies

The literature study conducted analyzed a few frameworks that have been developed to implement circularity principles. These frameworks, namely the Loops of Circularity and 10R Model of Circularity were explored and their idiosyncrasies were identified. While there are several other strategies conforming to the principles of circularity and numerous other examples of their application, this list below is a comprehensive representation of the principles of circularity that can be interpreted by consultants and advisors.

As mentioned in 3.1.6 Circular Principles and Frameworks**,** circular strategies conforming to loops of circularity that encapsulate the 10Rs have been elaborated below.

5.2.1 Narrowing Loop

5.2.1.1 Passive Design Strategies

Rethinking the need for an HVAC system for a building at the earliest point in the lifecycle of the project can reduce resource consumption throughout service life. Prioritizing passive measures right at the beginning is necessary considering the impact the location/site of the building and the use/occupancy have on the need for an HVAC system. These decisions are usually deliberated upon by the client and their representatives early on, during ***inception.*** Reducing or even eliminating reliance on mechanical ventilation can significantly reduce the consumption of energy, resources, materials, and environmental impact.

The following measures can be implemented for passive design strategies to execute the Rethink principles wherein the fundamental need for HVAC systems is questioned:

- A compact design reduces the surface for convection which reduces the convective heating demand. Therefore, the building shape and orientation significantly influence heating and cooling demand. Key designing methods like south-facing glazed facades (for the northern hemisphere) and Trombe walls can maximize the benefits of solar energy to reduce heating requirements during winter (Elaouzy, 2023).
- Trombe wall is a passive solar system made of dark-colored building materials and covered with vertical glass wherein ventilated air can circulate between the wall and the glazing. without needing a fan or a pump (Xiong et. al, 2022). This reduces the number of components required and subsequently the number of materials. Also, it does not consume any energy. They are of several types depending on application and climate.

- Thermal insulation design protects buildings from outdoor conditions by preventing heat gain or loss using the building's skin. Several materials like aerogels, mineral wool, EPS, XPS, fiberglass, cellulose, and calcium silicate can be used. The main challenge encountered in the selection of the right insulation material is the cost which is usually proportional to energy efficiency.
- Phase change materials play a vital role in increasing the thermal mass of the building's skin which implies better building performance. They are latent energy storage materials whose performance depends primarily on climate, the position of installation, and their melting temperature. Their use shows higher energy savings, lower GHG emissions, and lower embodied carbon.
- Green roofs and walls are a bioclimatic approach that usually comprises vegetation, substrate, filter, drainage layers, and insulation. They greatly increase a building's performance by decreasing the skin and interior air temperature thereby reducing HVAC loads. In winter, the vegetation acts as insulation whereas in summer it offers both shading and evaporative cooling. These design strategies can reduce energy requirements. However, they are not the most cost-effective due to higher initial, maintenance, and operating capital costs. The performance of these strategies relies on the configuration of the green surfaces, building characteristics like orientation, materials used for the skin, dimensions, shading, glazing area, and the local climate.
- Shading prevents buildings from transmitting solar radiation inwards. Techniques like overhangs, blinds, roller blinds, and roof shading like solar panels are being used. Again, the selection of this strategy depends on building orientation, layout, type, and climate. Shading performs best in cooling-dominated climates and is instrumental in controlling the daylight level.
- Natural ventilation is one of the most energy-efficient design strategies and its performance is influenced by climate, building features, and occupancy frequencies. It is a cost-effective solution that requires low investment, no maintenance, and no energy consumption. It can be used in combination with other strategies to improve its performance like glazing, insulation, and well-designed layout.
- Glazing is instrumental in controlling daylight levels, air infiltration, view, and shading in buildings. The selection of the right glazing depends on its properties and weather conditions. A carefully designed glazing system can significantly increase energy performance, reduce emissions, and be economically viable due to a shorter payback period.

In many scenarios, a combination of these strategies is required to achieve optimal thermal comfort and is a challenging task due to its dependence on building features (orientation, type, size, layout) and climatic conditions. Additionally, the cost-effectiveness also depends on the aforementioned factors, carbon taxation policies, and energy pricing (Elaouzy, 2023). An office building in Austria was built without any heating or air-conditioning technology which indicates that a high level of comfort can be achieved through passive heat gains and storage alone.

A mixed-mode strategy can also be developed to meet the project's requirements. Active measures can be taken in combination with passive design which can substantially **reduce** the consumption of materials, and energy. However, priority must be given to passive measures and the remaining demand can be powered by active ones.

5.2.1.2 Sharing Assets/Systems

Sharing spaces in buildings can **reduce** resource consumption and increase the utilization of spaces. Underuse of space is very unsustainable, and the space planning of a building has important implications on the selection of building services including HVAC systems.

Rethinking the functionality of a building during its lifecycle during ***inception and feasibility and planning*** to cater to multi-functional use cases allows the implementation of *centralized HVAC* infrastructure. Eliminating the need for separate units reduces the need for multiple systems/units which **reduces** the quantum of materials and optimizes resource utilization.

Designing spaces for sharing offers opportunities to design HVAC systems such that the heating and cooling load distribution is optimized. Analyzing potential occupancy patterns and thermal requirement zones for these spaces can **reduce** energy consumption. Systems like variable air volume units discussed before providing flexibility and precise control over such thermal zones.

Additionally, centralized systems responsible for large areas allow the implementation of waste heat recovery systems on a larger scale. HVAC systems release substantial heat which can be **repurposed** or **reused** for other heating purposes like water heaters or even provide heating to another area. It is not only a sustainable alternative but also increases the energy efficiency of the system.

Sharing of assets can also be achieved by *district heating and cooling*. It is known to positively contribute to a circular economy. They **reduce** primary energy consumption by utilizing **recovered** heat from industries, wastewater, and data centers and can be powered by renewable sources as well. Energy sources like biomass, geothermal, solar thermal, and green hydrogen can power district heating and cooling networks. Again, the centralized nature **reduces** materials used for standalone equipment and **reduces** carbon emissions to a large extent.

5.2.2 Slowing Loop

5.2.2.1 Product as a Service Model

Rethinking business models by expanding the focus from just monetary gains to promoting circularity is a crucial step that can be taken during the conduction of feasibility studies. Rethinking business models during ***feasibility and planning*** can be achieved by investigating options that can help recognize the value of circularity. One such business model is product as a service model.

Approaching suppliers earlier and allotting sufficient time for ***procurement*** allows consultants and the client to study the market for circular products and services and make conscious choices that align with their objectives. Conversations with suppliers ought to start earlier than the final design decisions have been affirmed since the market is still evolving.

Installation companies and manufacturers deliver a service to the client or the building owner and enter a fee-based contract as opposed to selling products. This arrangement transfers the risks of providing optimal levels of thermal comfort from the client to these companies/contractors and is incentive-based. Noncompliance with comfort parameters is a liability for these companies. This structure encourages these stakeholders to minimize failures and develop long-term cost-effective installations. Ensuring the longevity of installations/systems **reduces** the rate of replacement and subsequently consumption of resources and materials. On the flip side, the user or the customer pays the fee for comfort at a certain rate based on usage. The customer is incentivized to **reduce** energy consumption and save money in the process. Additionally, the manufacturer can utilize available data to recognize trends and deliver an efficient experience. For a monthly fee, they could ensure their systems experience no downtime and have a prolonged life cycle. With time, they can recover their investment in energy savings and efficiency whilst adding value to themselves, and the client.

With this model, providing a product as a service stimulates a more efficient use of the product. The manufacturers and installation companies can also take back the equipment at the end of life, which they can then **refurbish** for further use, **reuse**, or **recycle**. Service systems offer opportunities for circling natural resources for longer. Furthermore, keeping track of the equipment for updates and repairs intensifies customer relations. The user is interested only in the performance and reliability of the system and is indifferent to whether the product is new (Monitor, 2019).

5.2.2.2 Monitoring, Control, and Maintenance

Different technologies for monitoring and control can be analyzed for their compatibility with the proposed HVAC systems. The use of Building Automation Systems (BAS) and Building Management Systems (BMS) for maximizing energy efficiency, reducing failure rate, and prolonging the life of systems needs to be considered during ***feasibility and planning***. This is essential since it needs to be integrated with the building's design and infrastructure.

Subsequently, such systems need to be ***designed*** to seamlessly integrate with other systems including electric, data, and control interfaces. The infrastructure for monitoring and control needs to be scalable to allow the addition or expansion of monitoring points (HVAC systems, lighting, water, etc.) and their corresponding control systems as needed.

Developing a preventive maintenance program during ***use/operations*** helps identify potential issues that are mitigated before breakdowns. This prolongs the life of the asset and renders it functional for multiple life cycles. Monitoring the condition of the building components using efficient management systems can help identify opportunities for repair, refurbishment, or repurposing. Prioritizing **repair** and **refurbishment** over complete replacement can **reduce** waste and give the products a new lease of life. Maintaining an inventory of important spare parts helps facilitate timely repairs and reduces downtime.

Deployment of sensors to collect data on occupancy, indoor air quality, and energy usage renders real-time data to monitor resource consumption and building performance. With the collected data, a BAS/BMS system for centralized monitoring and control functions can automate HVAC operation and manage energy loads. This reduces the waste of energy and optimizes resource efficiency.

On the other hand, strict user control and the use of thermostats allows occupants to manage their thermal comfort preferences which not only improve comfort and well-being but also can result in minimizing energy wastage. User control can prevent strain on systems and prolong their lifespan. Relinquishing control to the user generates awareness about the energy consumed and can trigger a rethinking of energy conservation and sustainability.

To summarize, integrating BAS/BMS with user control and responsible thermostat usage can optimize energy efficiency and achieve thermal comfort.

5.2.2.3 Designing for Flexibility and Adaptability

During ***inception***, the brief developed for the project could entail the objective of *multiple functions over multiple lifecycles*. This limits immature demolition and offers new ways to maximize the utilization of the building.

Moreover, the building could be designed to have open and flexible layouts where all the layers of the building can be modified without adversely affecting the rest. Buildings designed for flexible use and with standard heights and dimensions can significantly contribute to **reuse**, **repurposing**, and increasing the longevity of HVAC systems. Also, refusing to structurally embed systems in other layers of the building ensures *easy disassembly and creation of demountable systems*. An example is dry underfloor heating and cooling systems. Using connections like bolts, screws, hangers, and brackets to install systems into the structural elements of the building ensures easy disassembly and accessibility. It increases the quality of maintenance and the potential for **reuse**. Refusing to use plaster, mortar, glue, and adhesives is recommended to maintain the quality of the material/components.

Creating flexible spaces facilitates easy reconfiguration and allows the creation of optimal HVAC zones. Precise control exerted due to specific thermal comfort needs in these zones reduces the need to condition underutilized spaces, the "grey areas". Additionally, flexible spaces render it easy to upgrade HVAC systems as they evolve and promote the integration of the latest systems without significant disruption to the other layers.

A flexible and standardized dimension layout is conducive to the development of modular HVAC units that can easily adapt to changing requirements. Maintaining standard dimensions ensures that HVAC units, ductwork, and other elements fit in their designated spaces and can also be reused or repurposed if a building is retrofitted. It increases the compatibility of these systems with other buildings as well without many modifications.

For HVAC systems, *modularization* can foster adaptation to changing needs. Known as the plug-and-play concept, HVAC units come with standard connections and *standardized* dimensions for their primary equipment, and distribution which enables compatibility with different configurations and building characteristics. Interoperability allows easy reuse/exchange of components across different projects. Modularity simplifies maintenance and components can easily be disconnected which does not require the entire system to be replaced. Targeted measures ensure easy refurbishments for specific components and ultimately prolong the life of the system. At their end of life, flexibility in connections makes it easy to disassemble them wherein different elements can be **reused, or repurposed**. Modular AHUs, rooftop packaged units, and heat pumps are a few examples of plug-and-play concept applications. The crux of this strategy is designing demountable and adaptable equipment. The table below summarizes the strategies discussed above.

	Strategies
Designing For Flexibility & Adaptability	Spatial Flexibility- Designing for multiple lifecycles for buildings
	Demountable systems for reuse and maintenance
	Standardized and Modular Equipment for repurposing and adaptability

Table 1: Strategies for Designing for Flexibility and Adaptability

5.2.2.4 Use of Prefabricated Equipment

The decision to use prefabricated equipment for HVAC installation in the ***early stages of design*** allows for more time for procurement and customization to suit project needs. It allows for better integration into the overall project plan. The manufacturing process and installation for prefabricated equipment involves less waste and is typically designed to be more space efficient which **reduces** structural requirement and less material usage. Moreover, it is designed for ease of installation and adaptability to accommodate future modifications and the flexibility reduces the need for major system replacement. Lastly, factory-controlled conditions result in better quality which reduces the likelihood of premature failure and maintenance is more straightforward due to standardized components resulting in **product life extension**.

5.2.3 Closing Loop

5.2.3.1 Reuse Components

Similar considerations need to be made for using reusable components and equipment for HVAC systems as those were made for biobased materials. Careful assessment of the compatibility of reused components with the proposed HVAC system design and determining the performance implications for energy consumption, maintenance requirements, compliance with regulations and cost-effectiveness, lifespan is necessary. It is vital to evaluate if the reusable components can meet the requirements or if modifications and additional components are necessary.

Rethinking a decommissioned or renovated building as a medium to harvest materials and components can contribute to keeping materials in a closed loop. Salvaging components and **refurbishing** them for reuse might require cleaning, repairing, and replacing worn-out parts. Hence, it is recommended during feasibility and procurement to search for ‘donor’ buildings and partner with secondary market owners which can fulfill demand and map out new streams to manage “waste”. This is applicable even for retrofitting a building wherein the components can be refurbished to perform the same function or even **repurposed** for a different application. Old steel or aluminum ductwork can be **repaired**, cleaned, and reused for another lifecycle in the same building or even for a new project. Old spiral ducts can be repurposed as façade cladding (Dokter, 2021). Ancillary components like grilles, duct support, pipe fixings, and other installations can also be repaired for reuse.

5.2.3.2 Mono-materialistic components

Similar considerations need to be made for mono-materialistic components during ***feasibility, procurement, and design*** as mentioned in the use of alternative/biobased materials.

Elaborating on the component and material level, **rethinking** the material composition can have a substantial impact on the recyclability quotient of a product and the corresponding energy requirements to do so. An example is the use of stainless-steel sheet or galvanized sheet steel for rigid ducts as opposed to ducts made of aluminum-coated glass wool, a popular alternative for their rapid installation, low price, and weight but its composite nature makes it very difficult to recycle.

Reducing or refusing to use pipes made of PE-RT, cross-linked polymers, and PPR for heat distribution due to difficulty in recycling. They consist of elements like glass fiber, aluminum, and other adhesive layers which makes it an energy cumbersome process to separate and recycle to furnish a product of the same quality. Even the use of paints or resins as a coating to prevent corrosion in radiators, air handling units, VAV boxes, grilles, etc. needs to be avoided since they reduce the material quality of the recyclate. It is, therefore, preferred to manufacture products and components that have no surface treatment (or use only C2C certified materials) which are easy to recycle. Ensuring material purity offers the opportunity for high-quality recyclate and the output can be **reused, repurposed, or remanufactured** to deliver optimal functionality.

5.2.4 Regenerating Loop

5.2.4.1 Low-impact/biobased materials

Using C2C-certified materials or equivalent materials is recommended for implementing circularity for HVAC systems and equipment. The market is still immature and needs development. With the advent of manufacturing processes and technological advancements, manufacturers can be encouraged to start developing products that can not only enhance their position in the market but also become more circular thereby triggering a **rethink** process.

Refusing to use products that originate from petroleum or other fossil fuels and including such criteria in tenders to ***procure*** suppliers reduces the environmental impact from emissions and during the manufacturing of such products. Again, it is important to allot more time to research the market and analyze alternative materials/products during ***feasibility, planning, and procurement*** to understand their performance characteristics, durability, and maintainability. It is pertinent that these materials meet functional requirements like strength, insulation, fire resistance, moisture resistance, and mold. For instance, failure to account for the impact of such materials on indoor air quality can impact health and safety since some biobased materials might release volatile organic compounds that diminish air quality (Braish, 2023). Furthermore, designers and engineers need to make design considerations for HVAC systems and other layers of the building for choosing to use alternative materials and their corresponding structural properties. For instance, some materials might require different dimension requirements and waste management systems (composting for biodegradable alternatives) compared to conventional options which need to be accounted for during the ***design*** phase.

A hazardous substance that is significant to cooling systems is the refrigerant. It is yet to have an efficient alternative that belongs to the biological cycle. However, it can be recycled and there are take-back contracts that can **refurbish** it to the same quality or **repurpose** it for other applications.

Refusing to use non-toxic materials in components can help prolong their life and promote **reuse**. This reduces the rate of replacement and optimizes resource efficiency.

Ecological insulating material like tamped hemp can be considered as an alternative. Another prospect could be BioFoam, an aerogel made of kelp and red algae. It is yet to find application in this industry but is gaining traction in food packaging. Cotton and denim insulation is an example of green alternatives that are almost always made of **recycled** materials. They make cellulose insulation an attractive option in the market. Cork insulation is known to have a negative carbon footprint and its resistance to mold and moisture infiltration makes it a very effective material. (Thermtest, 2023)

Air filters made of recycled textiles contain cellulose which is a sustainable alternative to disposable air filters that are often replaced faster due to contamination. (University, 2019).

5.2.4.2 Renewable sources

The decision to opt for renewable sources to cover the energy requirements of the building needs to be deliberated right during ***inception*** wherein the project goals and requirements are charted.

Rethinking the brief and corresponding objectives is essential for its consequential effect on the rest of the project's lifecycle, energy performance of the project, and achieving carbon neutrality.

Ideally, the energy demand of a building ought to be fulfilled by renewable sources that are produced on-site. It requires analyzing the site conditions, potential, compliance with local/building codes, etc. The use of renewable sources also has implications in the ***design*** phase due to space requirements, integration with the rest of the building, energy storage requirements, and local grid connections, among others.

It is necessary to achieve renewable heat coverage by employing the use of solar-thermal energy, geothermal energy, and active regenerative heating systems like heat pumps and CHP plants that are powered by on-site renewables. Such systems facilitate the **reuse** of heat that would otherwise be wasted. This also includes heating, cooling, and ventilation equipment that are electric but are supplied with renewable (preferably self-generated) electricity. Such active measures, in addition to passive measures discussed before, need to be integrated into buildings to abolish the use of oil and gas.

The upcoming illustration presents a clear and straightforward visual recognizing the strategies conforming to the resource loops mapped against the lifecycle phase they require consideration in. The beginning of each bar representing the strategy showcases that the application of the strategy requires consideration from that stage in the lifecycle. It is noteworthy to observe that all the strategies have been extended till "circulate" implying their potential to be reintroduced into the loop.

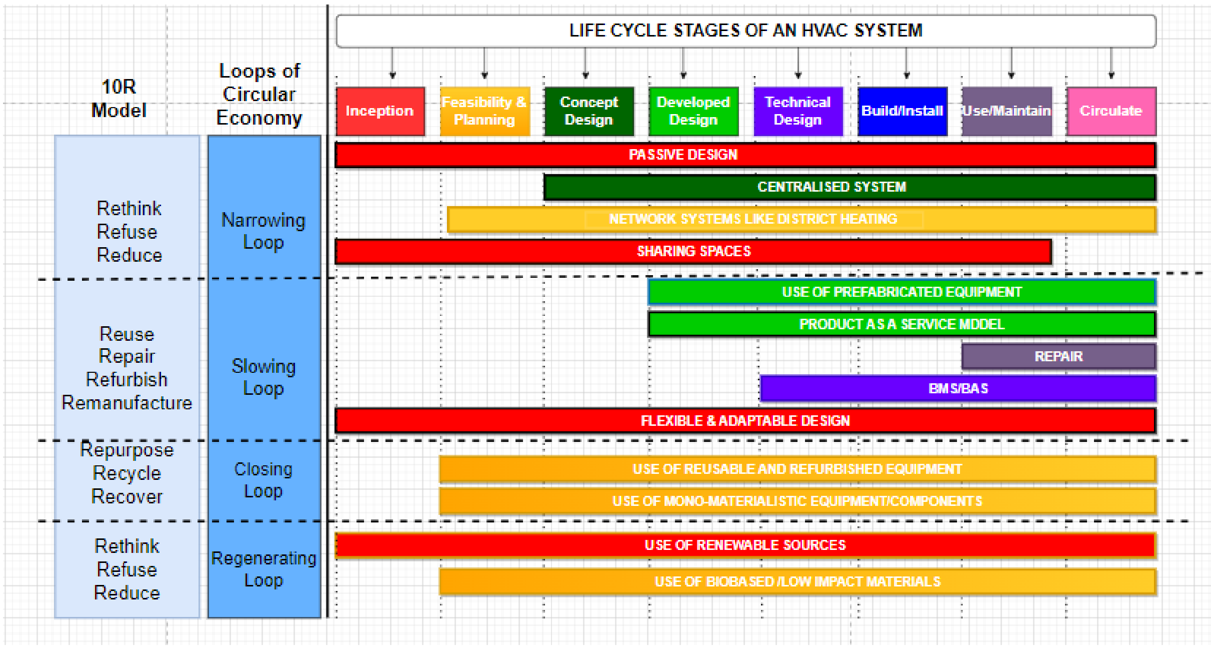

Figure 20: Lifecycle-Circular Strategy Mapping, own figure

5.3 Key Takeaways

This chapter elucidated a range of circular strategies, providing HVAC relevant examples and exploring their potential impact on various aspects of building design. Furthermore, the significance of considering lifecycle phases for strategy implementation was also emphasized. However, it is important to acknowledge that these findings primarily constitute theoretical concepts, albeit supported with practical examples. To gain a deeper understanding of their real-world applicability, feasibility, and the challenges and opportunities they present, interviews with industry-relevant stakeholders would reveal critical insights into the practical application of the recommended strategies. Finally, insights from these interviews represent empirical data, firmly rooted in industry practices and perspectives.

6. Data Analysis and Results

This chapter delves into the outcomes of the semi-structured interviews with stakeholders previously mentioned in **4. Stakeholder Analysis.** It is structured into two primary sections. The first one presents interview findings, categorized into three clusters. Section **6.1.1 Modifications to Lifecycle-Circular Strategy Mapping.** outlines the modifications suggested to **5.2 Circular Strategies**. This is followed by recommendations made by the stakeholders for collaboration required to influence change in HVAC systems in section **6.1.2 Key Roles & Responsibilities of Stakeholders**. Consequently, analysis of each stakeholder's perspective reveals opportunities and barriers affecting the implementation of the said circularity principles for HVAC systems is presented in section **6.1.3 Barriers and Opportunities.** Finally, potential changes in current HVAC systems due to the influence of circularity and the level of feasibility is a major outcome of the interviews, mentioned in section **6.1.4 Comparison of Circular Strategies against HVAC Evaluation Criteria.**

Section **6.2 Validation of Findings** elaborates on the insights and conclusions from the validation round conducted with experts to arrive at the final validated framework.

6.1 Key Insights from Interviews

This section presents the outcomes from interviews to gain insight into the practical feasibility, barriers, and opportunities for the proposed circular interventions for HVAC systems. For this purpose, stakeholders with abundant practical experience and expertise in the industry were interviewed. This lent authenticity to the findings and set forth a strong basis for conducting analysis. Each stakeholder interviewed was well-versed in the concept of sustainability and circularity in their practice. Below is a list of interviewees for reference:

Sr. No	Type of Stakeholder	Location
1.	MEP Design Consultant	Netherlands
2.	MEP Design Consultant	Netherlands
3.	MEP Design Consultant	Netherlands
4.	Client/Building Owner	Netherlands
5.	Manufacturer	Belgium
6.	Facility Manager	Netherlands
7.	Architect	Netherlands
8.	Architect	Netherlands

Table 2: Overview of Interviewees

The semi-structured interviews were analyzed thematically and explained in **2.2 Data Analysis**.

6.1.1 Modifications to Lifecycle-Circular Strategy Mapping.

The **5. Conceptual Model** delved into the various circular strategies that could be used to influence HVAC systems and potentially reduce their carbon footprint, both embodied and operational. It further presented insights regarding the optimal project lifecycle phase during which these strategies need to be considered for feasibility and most effect. Feedback from these interviews played a significant role in refining and adapting the proposed strategies to better align with the practical insights and needs identified during the interview process.

Strategy	Modification recommended
Network Systems	Given the reliance on service availability within the district the building is situated in, proactive considerations need to be initiated as early as the inception phase.
Flexible & Adaptable Design	A pivotal revelation was another method for crafting flexible and adaptable systems. This approach entails a deliberate effort to overdesign systems to accommodate potential future demand and slowing down the rate of premature replacement.

Table 3: Modifications to Lifecycle-Circular Strategy Mapping

The modified version of phase-wise application of circular strategies for HVAC systems is illustrated below.

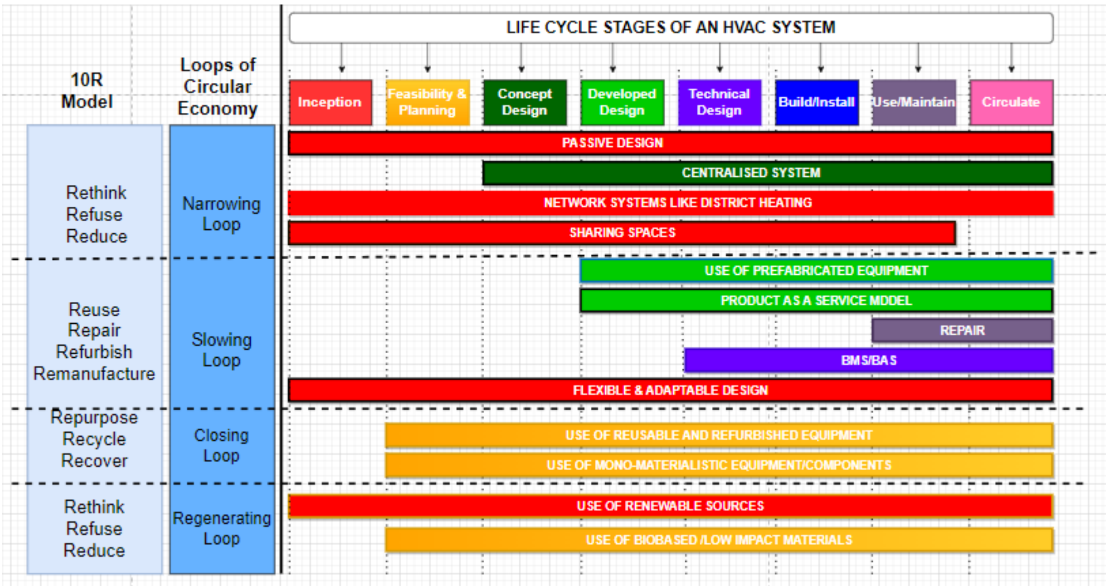

Figure 21: Modified Lifecycle-Circular Strategy Mapping

6.1.2 Key Roles & Responsibilities of Stakeholders

A significant outcome was insight into the diverse perspectives and their requirement for collaboration for adopting circularity within their capacity. This section explores distinct collaboration needs and responsibilities identified by each stakeholder.

Interviews revealed added functions within the existing supply chain network discussed in **4. Stakeholder Analysis**. They also necessitated diverse partners that can bring in new expertise, and experience and support the creation of a circular ecosystem for HVAC installations. Primarily, it is necessary to have extended collaboration albeit on different levels of involvement from the initial stages of the project.

Stakeholders	Responsibilities
Client/Building Owner	• Setting/approving ambition to include circularity and sustainability as one of the key objectives. • Envisage long-term vision for building considering future lifecycles as well. • Develop/approve ambition to reduce reliance on HVAC systems to meet building requirements
Architect/Design Team	• Develop design according to the client's circularity/sustainability ambitions. • Designing spaces with considerations for future modifications in services. (Avoid narrow spaces for technical services) • Collaborate with MEP consultants, Building Physics consultants, and other stakeholders to incorporate passive design strategies.
MEP and Building Physics Consultancies	• Involvement with clients from inception to help them develop circular and sustainable ambitions regarding MEP services. • Advise/convince client on best practices and alternatives to primary materials/systems. • Emphasize on feasibility and benefits of passive design and flexibility for buildings and concurrently, HVAC systems. • Investigate the availability of alternative materials, reused/refurbished equipment, and mono-materialistic components to design HVAC systems. • Involved in future evaluation of the building's performance. • Collaborate with the design team, facility managers, urban mining bodies, and contractors to apply circular strategies from the early stages.
Facility Managers	• Provide expertise in the selection of systems designed for longevity, ease of maintenance, reduced replacement, and disassembly. • Ensure longevity, performance, and reliability of reused equipment during use through monitoring and maintenance. • Collaborate with urban mining companies to render a new lease of life for used equipment.
Manufacturers and Suppliers	• Consult clients, design teams, and consultancies in the initial stages to integrate innovative solutions. • Provide information on products that are modular, designed for prolonged life, and easy to disassemble to influence system design. • Inform about building codes and the feasibility of using reusable products. • Share knowledge about circular products for better material selection and waste reduction in the initial stages.
Contractors	• Use their knowledge of the market and materials to design systems that have prolonged life spans and can be reusable/refurbished. • Develop strategies to minimize waste during construction. • Harvest equipment/materials instead of demolition.
Secondary market owners/urban mining	• Be involved during feasibility and planning to provide information about available materials and equipment.
Circularity/sustainability Consultants	• Help the client develop a comprehensive circular strategy for the entire building. • Collaborate with the design team and MEP consultants to strategize best practices for circularity in this layer of the building and inadvertently, the other layers as well. • Educate and engage stakeholders involved in the project.

Users	• Engage with users through interactive workshops early on to understand their needs (including occupancy patterns and behavior) and tailor system design to meet their demands more efficiently. • Generate awareness and educate users about the importance of saving energy.
Energy Suppliers	• Promote the use of renewable energy sources and network systems like district heating/cooling. • Collaborate with building owners and consultants to identify energy-saving opportunities. • Provide information on cleaner alternatives and incentives for sustainable practices. • Monitor and evaluate energy performance of buildings and HVAC systems.
Other Experts	• Knowledge sharing on various matters like materials, waste management, biology, ecology, etc. with other stakeholders early in the life cycle.

Table 4: Expanded Roles for Stakeholders

6.1.3 Barriers and Opportunities

This section yields the answer to SQ4 of this thesis. Every stakeholder had a very exclusive perspective on the current level of circularity, factors impeding the traction, and their vision of what is required for circular economy to achieve its potential in the future. The barriers have been organized into themes they represent and are listed below.

6.1.3.1 Barriers

6.1.3.1.1 Technical Barriers

There are apprehensions regarding the functionality and added value of circular equipment and systems on account of lack of evidence. As stated by Interviewee 3, *"It is difficult to recommend biobased materials' pipes for distribution because it is still inconclusive whether they can deliver specific temperature and pressure requirements."* Interviewee 6 concurred and added, *"Biobased materials did not live up to the hygiene standards that need to be upheld, at an exhibit I attended for alternative materials in construction."* This is especially important for HVAC systems since their primary objective is to offer a safe indoor climate for its occupants. Furthermore, Interviewee 6 also said, *"lack of knowledge about biobased materials makes maintaining it difficult and we cannot guarantee the quality of the product thereafter."* Interviewee 3 says that there need to be guarantees or certificates that promise the reliability of such products and that there need to be official guidelines on how such materials can be used.

Additionally, the specificity of HVAC system installation goes against the principles of circularity. As articulated by Interviewee 7, *"HVAC equipment is designed to be very specific, and specific and sustainable are like enemies."* As corroborated by Interviewee 5, *"the standards and specifications about pipes and other installations make it difficult to use donor building's equipment."* The specific design of the installations to deliver optimum performance requires a mix of materials which are often difficult to separate and energy intensive. For example, pipes for sanitary systems have a mixture of polyethylene and aluminum to deliver higher temperature and pressure requirements. This is also used for underfloor heating pipes; it is not needed but is still often used. Another example is the treatment of primary equipment which is often made up of copper, steel, and aluminum for separation and reuse. It is difficult, energy-intensive, and expensive.

Another significant finding that inhibits the reuse of old components of HVAC systems is the problem of compatibility of old components with new system connections and installations as stated by Interviewee 4. They also gave an example citing, "It is possible to use an old casing for an Air handling Unit, but it is often observed that it is not possible because the newer parts comprising an AHU are much bigger and cannot fit within the casing." This resonates with the problem of specificity as well. Furthermore, the loss in efficiency of old equipment with time needs frequent replacement of parts and cannot compare against the newer technology, impeding reuse.

Lastly, spatial constraints are significant in slowing the uptake of flexible and standardized systems. As per Interviewee 1, *"Architects make space for technical services as narrow as possible which reduces the possibilities for standardization and future modification."* This is also seen in the adoption of on-site renewable sources. Interviewee 4 states, *"Circularity needs a lot of room to implement, for example, having solar panels needs significant space within the premises."*

6.1.3.1.2 Economic Barriers

As per interviewee 1, *"Circularity is difficult to implement if one is profit driven and not value driven."*

"It is much more expensive to reuse old equipment currently because it is cost, time, and labor-intensive to harvest materials and equipment, sort them, and refurbish/repair them than to demolish the building and its components" as stated by Interviewee 1.

Currently, it is much cheaper to just buy new equipment instead of buying used components. Primarily, the availability of such is higher and there is greater demand for it. Contractors prefer using newer equipment because they are used to the ways of working with such equipment and clients prefer to invest in them because there is an apprehension to using used equipment and components. The optics of reusability are bad; people think used components are not reliable or clean. On the supply side, there is a lack of donor buildings to furnish used components and there is little awareness about the presence of secondary material marketplaces that trade such assets. So, supply and demand favor the use of newer equipment.

Additionally, Interviewee 5 said, *"Owing to the niche of this market currently, there are not many people engaging in circular practices in manufacturing. Circularity is not seen as a USP (Unique Selling Point) yet and we do not see a competitive advantage if we do it."*

However, as per interviewee 4, *"Despite the expense, people have to do it."*

6.1.3.1.2 Legislative Barriers

The interviewees were questioned if there were any legislative rules or regulations that could offer impetus to circularity for HVAC services in buildings. Additionally, the presence of said rules and regulations that might slow the adoption was also questioned.

As per Interviewee 1, "*Regulation dictates that a few things must be replaced and cannot be reused."* This was also reiterated by Interviewee 7 who said, *"The codes and compliances are being developed and redeveloped to become safer and more stringent."* Such specific mandates have implications for the adoption of passive design strategies to reduce the need for mechanical systems. There are standards developed for utility buildings like office buildings, and hospitals that require HVAC to meet the occupants' thermal comfort requirements.

Most of the interviewees concurred that regulations need to mandate the reuse of installations to encourage circularity in this layer and ensure the availability of funds and resources to facilitate this.

6.1.3.1.3 Social/Organizational Barriers

Interviewee 4 made a very relevant observation about the sharing of spaces to reduce resource consumption. He said that despite the best intentions of the building owner to lease office floor spaces to other organizations to encourage complete use of the building and reduce the need for more, it is quite difficult to lease more than 15%-20% of the total space. He added that organizations often prefer to have their own space and many organizations work with data, often sensitive, and would rather not have employees from other companies in proximity.

To encourage flexibility in buildings would require a shift in the mindset of people in addition to design considerations. This is a slow, evolutionary process that has begun but needs some rules and regulations to garner momentum. It would be a redundant effort if there were no takers for such shared spaces.

Often, clients or building owners do not have enough knowledge of ways the project could be made more circular and rely on consultants to inform them of the best alternatives. For instance, Interviewee 4 mentioned that he needs his advisors to tell him the importance and benefits of using reusable components and that he relies on them and installation companies to persuade him.

The lack of knowledge is observed even by Interviewee 1 who said, *"There is not a lot of knowledge about which systems or which materials are the best ones to use. We need to know replacement for current options and the associated costs."* In consonance, Interviewee 3 observes that he needs to know what circular solutions are available, how they can be used, and their impact. If this is known, one can design better solutions and it would be a good step towards circularity.

This is one of the primary objectives of the research to provide a comprehensive list of circular solutions and how they can potentially improve HVAC systems or even reduce the need for them.

6.1.3.2 Opportunities

In addition to barriers, stakeholders also recognized opportunities and suggestions on measures conducive to the inclusion of circularity measures for HVAC systems. They have been described below.

Primarily, there is increased awareness about the future scarcity of materials and the consequent increase in the prices of primary materials. Interviewee 5 exclaims that there is no option but to adopt reuse practices and other circularity measures to futureproof the industry. He described this near-future event as the present-day oil price crisis that affected the world and boosted the sale of electric cars. It is now a new normal. He believes future volatility will force us to adopt circular practices.

He further added that the scarcity of materials and climate change could result in regulations from the government that could render manufacturers and suppliers of primary material equipment obsolete. They want to safeguard themselves against redundancy by already looking into sustainable alternatives.

This can bolster the concept of sustainable and circular practices. With adequate knowledge of circular interventions and alternatives for current options and their influence on HVAC systems, it can serve as a good starting point.

Also, the energy crisis and rising prices of oil, gas, and coal are good grounds for buildings to explore sustainable sources like on-site renewables, and district heating/cooling from renewable sources and implement measures that reduce energy consumption. Given the rising prices and a new policy requiring offices to have at least an energy label C from January 2023 will drive decisions that include sustainable and circular design. There are requirements to be met under the same decree for HVAC installations such as boilers and air conditioners. This decree requires measures that reduce carbon emissions and energy-saving measures, a mandate conducive to circular interventions. As iterated by Interviewee 4, a client wants a higher energy label than the building currently has, is retrofitting the existing building to create a shared space office building and looking to invest in building circular installations. He says this regulation is a good starting point to invest in solutions that have a long-term goal that includes sustainable and circular ambitions.

6.1.4 Comparison of Circular Strategies against HVAC Evaluation Criteria

At large, the sentiment observed through the analysis of interviews reveals that all the stakeholders agree that there is a lot of potential for circularity but is still nascent. A significant realization was that while a circular economy has immense scope for value creation, there are disadvantages to it, requiring trade-offs that are reflected in its implementation and level of feasibility. This research aims to address if circular strategies are exercised, how they influence current HVAC systems and what are the benefits and trade-offs to be made to apply them. Comparing circular HVAC systems against performance evaluation criteria can provide a comprehensive assessment of how well circular strategies align with performance standards, economic considerations, environmental goals, and regulatory compliances. This holistic evaluation also informs stakeholders about the feasibility of implementing circularity in HVAC systems. The first step to understanding the implications of current HVAC systems was to identify circular strategies that are currently applicable. This is primarily for MEP consultants who would like to know about current circular solutions and how they can be applied. These strategies have been elucidated upon in the **5. CONCEPTUAL MODEL**.

After gaining an understanding of the circular strategies that can be applied, their influence on HVAC systems will be examined by comparing them against conventional systems wherein no circular

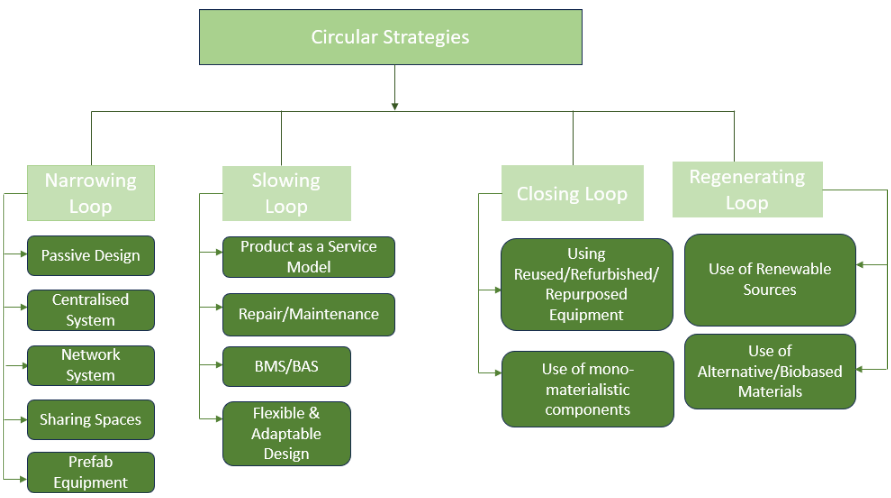

Figure 22: Circular strategies categorized into loops of circularity. Own figure

strategies are applied. These criteria were discussed at length and categorized into broad characteristics in the section **3.2.5 What are the Evaluation Criteria for HVAC Systems?**

1. Using Passive Design Strategies

Passive design harnesses the natural principles to regulate indoor temperature, lighting, and ventilation without relying on mechanical systems to create energy-efficient, comfortable, and sustainable buildings. More information regarding ways of passive design can be found in the **5. Conceptual Model**. Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It has relevance to all the factors, ergonomics, cost, technical properties, physical properties, flexibility, and reliability.

- Ergonomics: While passive design strategies can offer comparable levels of ventilation, humidity control, and thermal comfort, their effectiveness may vary based on the building's location, orientation, and design. Another shortcoming of passive design is the limited scope of immediate and adjustable temperature and humidity control. A hybrid approach can limit this drawback and reduce reliance on HVAC.
- Costs: While passive design strategies might require more upfront costs during construction as opposed to conventional HVAC systems that typically have a standardized installation process, the lifecycle costs could be lower. It is more cost-effective due to reduced energy consumption and lack of mechanical equipment.
- Technical Properties: This strategy reduces water and energy consumption compared to conventional systems. Consequently, carbon emissions are also reduced. Conventional systems offer more precise control over temperature and air distribution as opposed to passive design which takes a more holistic approach to thermal regulation involving the entire building.
- Physical Properties: This principle affects the entire building including the envelope, design, and location of windows which may affect the available wall space and thicker walls. However, the reduced mechanical equipment for installations might reduce the space requirement for mechanical rooms. Concerning appearance, passive design involves green roofs, green walls, well-placed windows, aesthetic solar shading, etc. that might uplift the visual aesthetic of the overall building.
- Flexibility: It might be more complex to install some passive design features if not done so during construction whereas HVAC systems can be easily installed in both new and existing buildings. Additionally, this design principle is very dependent on local climate and occupant needs, which might render it difficult to integrate with every kind of building. However, they do not require a lot of maintenance compared to mechanical systems.
- Reliability: Most passive design features have a long lifetime, almost as long as the rest of the building. However, currently, there are not many vendors or in this case, design teams/contractors undertaking such projects focusing on this design strategy.

Currently, the building codes and regulations require mechanical ventilation for utility buildings and complete reliance on passive design is not possible. While some features like glazing, insulation, and shading devices are employed, the feasibility of exercising this strategy remains low due to inconsistent temperature, humidity control and regulatory provisions.

2. Centralized Systems

This strategy aims to increase resource efficiency by replacing separate, decentralized systems for different services like heating and cooling. More information regarding this strategy can be referred to in **5. Conceptual Model.** Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on costs, technical properties, physical properties, flexibility, and reliability.

- Costs: Centralized systems might require higher upfront costs due to higher capacity to serve multiple zones. However, the lifecycle costs could be lower due to improved resource efficiency and economy of scale.
- Technical Properties: Centralized systems generally consume less water due to efficient water-cooling methods like cooling towers or employing water recycling systems as opposed to water-cooled chillers which consume more water. These systems can also achieve higher resource efficiency through economy of scale and an optimized design that reduces energy consumption. However, these systems have limited control zones. This can result in limited personalized temperature control or building. This has other implications since "grey zones", places with limited activity or fewer occupants will still be air-conditioned despite no need and lead to higher resource/energy consumption. However, this can be offset by control systems and user control.
- Physical Properties: These systems often require considerable area for equipment and distribution, more than required for conventional systems. Often the central equipment is housed on the rooftop or in a designated space which can be considered during the design of the building.
- Flexibility: The installation of centralized systems could be more complex and time-consuming, especially for large-scale projects, and might require specialized labor for installation and maintenance. However, it is possible to integrate such systems with various energy sources like district heating, renewable sources, etc. This flexibility is a bit constricted with decentralized HVAC equipment that is usually designed for specific energy types and might require complete replacement to adapt to changes in energy prices or accommodate sustainability (gas boilers). On the flip side though, it is much more complex to adapt centralized systems to evolving needs of the building. It could imply significant changes to the distribution network. The level of flexibility depends on the client's ambition. If it is clear, it can be accommodated early on.
- Reliability: Considering the complexity and scale of such systems, the availability of spare parts for such equipment might be a concern. Moreover, due to the complexity, equipment failure can require more repair time and more downtime consequently. However, these systems are often designed for longevity and have a longer lifetime. Moreover, this equipment is quite expensive, so it is in the interest of the facility management and the building owner to prolong the life of the equipment with proactive maintenance.

Centralized systems are widely used for utility buildings owing to their capacity and demand. With efficient control systems and user control, the risk of higher energy consumption can be mitigated rendering it highly feasible to apply.

3. Employing District Heating/Cooling

District heating/cooling are centralized energy distribution systems that offer heating or cooling services to several buildings within a district. If their energy sources are renewable i.e., solar, wind, geothermal, biomass energy, etc., it is a very sustainable and cost-effective solution. More information regarding this circular strategy can be found in the **5. Conceptual Model.**

Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on costs, technical properties, physical properties, flexibility, and reliability.

- Costs: Contingent on the availability of a district heating/cooling system in the building's district/area, connecting to the system might result in lower capital costs and the client might not need to invest in heating/cooling primary equipment but for distribution and release systems within the building only. It could also imply lower maintenance costs and overall lifecycle costs due to improved energy efficiency and optimization of resources.
- Technical Properties: The use of district heating/cooling does not have a direct implication on water consumption compared to conventional HVAC systems since they both use significant water for operation. Carbon emissions are lower if energy sources are renewable. Energy consumption could be lower than conventional HVAC systems due to centralized energy production. Lastly, personalized thermal control is constrained due to the centralized nature of these systems. Again, it can be offset by control systems.
- Physical Properties: The use of district heating/cooling systems might free up space usually required for primary equipment in the building. However, it might require more distribution material like pipes or ducts to deliver it to the building.
- Flexibility: Setting up this requires extensive collaboration with the district operator, building owner, contractors, etc. to connect the district system to the building's distribution and release systems. Integrating this connection with the building installation might involve upgrading or replacing the existing building infrastructure.
- Reliability: This system's applicability is completely dependent on the location of the building as opposed to conventional systems that have a wide availability of manufacturers and spare parts. Also, failure or breakdown of the equipment can be critical since it can affect the building services of the entire area and the scale of the system might require more time for repair.

The share of district heating networks powered by renewable sources and residual heat is increasing but its feasibility depends on the availability of the service for that building and the demand for heat. As a result, it is not the most feasible strategy. However, National climate goals require an increase in the share of district networks to enhance sustainability which can increase the level of feasibility.

4. Sharing of Spaces

This approach promotes an efficient use of resources, reduces waste, and involves multiple users or functions using the same assets. More information can be found in the **5. Conceptual Model**.

Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on ergonomics, costs, technical properties, physical properties, flexibility, and reliability.

- Ergonomics: While multiple activities and fluctuating number of occupants might influence thermal comfort and ventilation, careful design and efficient control systems can help achieve an ideal indoor climate comparable to the efficiency of an otherwise conventional design.
- Costs: The complexity corresponding to the design of shared spaces might incur additional costs in planning and designing HVAC systems for shared spaces. These costs might include investments in adaptive ventilation systems. However, it can be offset by potential energy savings and resource efficiency. Moreover, it mostly would employ a centralized system whose implications were discussed previously.

- Technical Properties: The sharing of assets implies reducing the number of resources which translates to lower emissions and embodied carbon. Furthermore, centralized equipment's limitation of restricted personalized control can be corrected with smart control systems.
- Flexibility: Spaces designed for shared use imply flexible systems as well. However, it might translate to extra provisions and overdesigning systems including primary equipment, distribution, and installations to meet the varying demand. However, it is much more flexible than conventional design which is often rigid to cope with evolving needs. Additionally, designing shared spaces ensures that all the building services are integrated seamlessly into a single building management system.
- Reliability: There is no direct implication on this criterion. Factors relevant to centralized systems apply to this principle as well.

Essentially, it requires the use of centralized systems, extra provisions for personalized control, and more thermal zones that could include VAV Boxes, valves, and more. This is a prevailing practice that signifies high feasibility. However, as mentioned in **6.1.3.1.3 Social/Organizational Barriers,** apprehension towards sharing spaces by organizations can affect the feasibility and reduce its applicability. Having said that, the concept of coworking spaces and multipurpose facilities offered by hotels is on the rise implying more takers for this concept.

5. Use of Prefabricated Equipment for Generation, Distribution and Release Systems

Prefabricated equipment means that the manufacturing and/or assembly of the components is done offsite and then installed. It is an efficient process aimed at minimizing waste and often produces standardized equipment. More information regarding this strategy can be referred to in the **5. Conceptual Model**. Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on costs, technical properties, physical properties, flexibility, and reliability.

- Costs: The upfront costs could be higher than conventional equipment due to the costs associated with sophisticated manufacturing (could be additive manufacturing), transportation, and assembly. However, prefabricated equipment is often designed with a standardized process which could reduce maintenance costs.
- Technical Properties: It is unclear whether the carbon emissions from using prefabricated equipment are lesser than using conventional equipment. While such equipment often has a longer life with less need for replacement and less material is wasted during manufacturing, the logistical supply chain, and emissions due to operation also need to be factored in. However, prefabricated equipment can be designed to produce lighter structures which implies less consumption of resources.
- Physical Properties: Prefabricated equipment often yields lighter and more compact structures which reduces the area requirement and is more aesthetically appealing due to a more cohesive appearance. While this could look boring, it is a fair trade-off since they are technical installations.
- Flexibility: Prefabricated equipment is designed for ease of installation and is standardized, which increases its compatibility. It can be repurposed post-renovation or even for other buildings. Moreover, its ease of installation can be leveraged to disassemble it for reuse too. Moreover, the standardized process of manufacturing and design makes the maintenance procedure quite standard as well which makes it easy for technicians to conduct repairs and could potentially not require specialized technicians.

- Reliability: Their construction ensures a longer lifespan and could be refurbished to serve for longer. The ease of maintenance and standardization translates to less time required for repair and downtime. More and more manufacturers are foraying into this kind of manufacturing and standardization also ensures easy availability of spare parts.

Current HVAC systems comprise equipment like AHUs, Ductwork, pipe networks, humidifiers, and more, which are already prefabricated. The characteristics mentioned above make them highly suitable for implementation.

6. Product as a Service Model

The product-as-a-service model encourages manufacturers to design products for longevity, ease of maintenance, and efficiency. More information regarding this strategy can be referred to in the **5. CONCEPTUAL MODEL**. Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on costs, technical properties, flexibility, and reliability.

- Costs: The upfront costs are usually lower than for conventional business models considering the client/building owner pays a service fee spread over a certain time. This also includes the maintenance fee.
- Technical properties: The incentive to minimize operating costs by the manufacturer/installation company might lead to higher energy efficiency and a higher performance of systems. However, conventional HVAC contract types could also offer higher energy efficiencies.
- Flexibility: Considering the expense of maintenance and installation is borne by the manufacturer, they are more likely to develop systems that have less repair times, and that are easy to install. Moreover, it is in their vested interest to install systems that can be upgraded and are flexible to continue as the service provider and meet the building's evolving needs.
- Reliability: Again, the contract type incentivizes the service providers to prolong the life of the systems and reduce downtime delivering reliable systems. However, currently, not many manufacturers are adopting this business model to avail this facility.

Product as a service model is currently available for select systems like for pumps, air conditioning (cooling as a service), and facades. While this model demonstrates good performance against the criteria, it is important to acknowledge that its availability is somewhat limited. As a result, the overall feasibility of adopting this approach is good but not without its constraints.

7. Repair/Maintenance

This strategy focuses on prolonging the life of systems and equipment. Considering the implications of this strategy is essential due to the significant costs it incurs throughout the lifecycle of the asset. In the long run, costs for operation and maintenance cost about 50-80% of the lifecycle of the system. More information regarding this strategy can be referred to in the **5. CONCEPTUAL MODEL.**

Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on costs, technical properties, and reliability.

- Costs: Continuing to use the same equipment with regular and proactive maintenance with intermittent repair to avoid breakdowns translates to lower costs incurred as capital expenditure if the equipment is replaced. Moreover, this strategy is employed in general.

Hence there is no big jump in lifecycle costs as well. However, the cost savings and product life extension depend on how old or functional the equipment is.
- Technical Properties: Efficient use of this strategy indirectly reduces carbon emissions. There is a lower need to buy new products which reduces embodied carbon. It also has a direct implication for emissions due to operation. An efficient system can reduce energy consumption and emissions and improve performance. However, it is unclear if its impact on energy efficiency is greater than a new system that has a higher energy efficiency and performance rating. However, integrating this strategy with new equipment implies that it will minimize the need to replace it soon.
- Reliability: The repair time for this activity is comparatively quicker as compared to the full replacement of the equipment and installation of a new one, which significantly reduces the time required. This also implies fewer disruptions for occupants if it is an existing building. Additionally, repair and maintenance can significantly improve the lifespan of the system and there is a huge landscape of contractors and maintenance services so there is flexibility to choose from the market.

It is a prevailing practice exercised for every project and type of system demonstrating a high degree of feasibility to implement as a circular strategy designed for product life extension.

8. Integration of Building Management Systems/Building Automation Systems

BMS/BAS are integrated systems that monitor, control, and optimize building services like HVAC, and lighting. Much like repair and maintenance, these systems accrue significant costs and require sophisticated infrastructure. This is why it is important to understand how their integration influences HVAC performance. It has implications on ergonomics, costs, technical properties, flexibility, and reliability.

- Ergonomics: These systems use real-time data to monitor the activity and needs of occupants. This translates to a better indoor climate.
- Costs: The upfront costs of these systems and their integration can be higher due to installation costs, and the extra equipment required. Furthermore, there are costs associated with the maintenance of these systems in addition to the services. However, operation costs might be lower due to more efficiency and optimized consumption.
- Technical Properties: These systems are designed to optimize resource consumption including water and energy. Moreover, reduced energy consumption implies lower emissions during operations, and the prolonged life of equipment due to these systems ensures a longer life thereby reducing the need for frequent replacement i.e., lower embodied carbon. Finally, one of their primary features is more granular control to optimize services and cater to occupant needs. Ultimately, the integration of such systems can outperform HVAC systems without them.
- Physical Properties: The infrastructure might require some additional room, but the benefits of automation and management could outweigh the area requirements.
- Flexibility: Installation of BAS/BMS requires specialized technicians and could be a complex process. Moreover, considering its integration with several technical services in a building, it adds another dimension of complexity. However, it offers a seamless integration for all the building services.

  For existing buildings, however, the process is even more complex. Notwithstanding the possibility, it requires careful consideration of the compatibility of the existing systems with this infrastructure, and upgrades to the existing building infrastructure to ensure good integration.

- Reliability: Implementing this strategy could mean proactive maintenance, reducing breakdown, quicker diagnosis, and improvement in repair time. This also translates to a longer lifespan. There is a considerable market size offering installation and maintenance services for these systems.

Many manufacturers are offering this service and is a prevailing practice for utility buildings for personalized control and reducing energy consumption. Additionally, advancements in technology to employ data and IoT indicate a high degree of feasibility.

9. Flexible and Adaptable Design of HVAC Systems

Designing flexible and adaptable HVAC systems can improve resilience to the building's evolving needs even if they are to be used in another application/building. It reduces the need for replacement and can be used seamlessly for flexible buildings as well. Flexible and Adaptable Design includes designing for modularity, overdesigning for future modifications/increase in demand, and integration of sophisticated control systems to make provisions for changing thermal zones. It is effective if the systems are used for posterity and the client has a long-term vision to use the building "endlessly" even for different functions if need be. If not, the resources, materials, and infrastructure added to cope with future changes would be against the principles of circularity and exhaustive.

Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on costs, technical properties, physical properties, flexibility, and reliability.

- Costs: The added infrastructure to offer flexible thermal zones, and overdesigning equipment to meet future demand translates to higher upfront costs. However, overdesigning for future modifications is not that expensive for heating/cooling. Primarily for cooling, it potentially is not even an "added cost" as it is almost necessary to overdesign to develop resilience against climate change. Moreover, procuring standardized and modular equipment could also imply more capital expenditure. However, the ease of maintenance due to modularity could bring down costs. Installing demountable systems could imply higher costs for installation and the attach-detach process could entail higher labor costs.
- Technical Properties: Designing flexible and adaptable systems for flexible and evolving requirements of a building does not have a direct impact on water or energy consumption. Considering the reduced rate of replacement, it reduces carbon emissions. However, overdesigning systems for primary equipment might lead to higher energy consumption if the system operates with excess capacity for current needs and consequently raises operating costs. Finally, it provides more granular and flexible control zones.
- Flexibility: such systems can be installed easily due to their modularity and the standard production implies a standardized installation procedure. The standardized equipment and connections ensure seamless integration. Old equipment can be supplemented with new equipment for the increase in demand (future proofing). Extra provisions can be made for piping and distribution to meet future demand. For example, T-valves and flexible sections for air ducts that can easily be extended to supply conditioned air offer more thermal zones and reconfiguration.

- Reliability: The characteristics of such equipment are designed for prolonged life. The market for demountable and standardized equipment is increasing significantly which ensures the availability of manufacturers and spare parts.

There is a wide availability of manufacturers offering modular solutions for HVAC systems along with a growing practice of designing and installing demountable equipment. Although it is potentially more expensive to install for the contractor, the ease of maintenance and reusability is a good incentive. This denotes a high degree of feasibility.

10. Utilizing Reused/Refurbished/Repurposed Materials/Equipment

This is one of the key principles of Circular economy; ensuring materials are in a closed loop and reducing carbon footprint. However, it is critical to know if the material/component being reused is safe and non-toxic. This is especially important for HVAC systems as they directly impact the health and well-being of occupants. More information regarding this strategy can be referred to in the Conceptual Model.

Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on ergonomics, costs, technical properties, physical properties, flexibility, and reliability.

- Ergonomics: If the design, maintenance history, and compatibility with the building's requirements align with the used equipment, there is no direct influence on the ergonomics of the system. This is contingent on the cleanliness and non-toxicity of the equipment being reused or repurposed.
- Costs: The upfront costs are often higher in the current market due to high labor costs and there is no economy of scale yet. Furthermore, the maintenance costs could also be higher considering its longer lifespan and condition. The operating costs might also be higher due to lower efficiency compared to newer equipment. However, it depends on the type of equipment as well. Components like fans, coils, and condensers might lose efficiency with time and cannot outperform new equipment as opposed to pipes, ducts, and central equipment like AHUs and heat pumps that can work efficiently with the repair and replacement of their constituent parts.
- Technical Properties: While the efficiency of used equipment could be lower than the latest technology if the equipment was maintained well and necessary repairs and replacement of parts were done in its previous lifecycle, the loss in efficiency is manageable. There is no risk in using such equipment concerning its efficiency and performance. For instance, an air handling unit is completely reusable if it is regularly maintained and its constituent parts like filters or coils are repaired or replaced if it is not at all salvageable.
- Physical Properties: There is no significant impact on the physical appearance or space requirement if this strategy is applied as compared to conventional systems. The appearance of previously used systems could reinforce the aesthetic of a sustainably constructed building.
- Flexibility: This strategy falters regarding integration flexibility. There is a risk of the incompatibility of older equipment with the latest equipment and connections. However, for all new equipment, if their dimensions and connections are standardized, this drawback can be mitigated to ensure seamless integration for all equipment, new and old.
- Reliability: The lifespan of the product is congruent with its maintenance history, age, and condition. It could be lower than its counterpart, new equipment. Furthermore, the

availability of spare parts and vendors selling such equipment might affect the reliability of such equipment.

While the level of feasibility for reusing heat pumps, AHUs, and even heat distribution pipes can be more, the feasibility of this strategy depends on the availability of appropriate reused equipment, computability, and the condition. This affects the level of feasibility.

11. Use of renewable sources

This strategy aims to reduce and ultimately eradicate the dependence on fossil fuels which have a huge environmental impact. More information regarding the same can be referred to in the **5. Conceptual Model.** Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on costs, technical properties, physical properties, flexibility, and reliability.

- Costs: The upfront costs could be higher than conventional gas/coal run equipment. However, the market has grown exponentially and there are numerous options, so this translates to decreasing upfront costs. However, for onsite renewables and regenerative systems, the upfront costs could still be higher. The operating and maintenance costs can offset the initial investment and can be even cheaper than conventional systems throughout the lifecycle. Also, governments offer tax benefits to encourage the adoption of renewable energy which could lower costs.
- Technical Properties: Conventional systems consume a lot of water and energy for their function as opposed to systems powered by renewable energy. Moreover, renewable energy produces electricity with no direct carbon emissions significantly reducing the building's carbon footprint.
- Physical Properties: on-site renewables require additional space depending on the location, energy demand, capacity, and availability of energy source. The space required could be higher than for conventional systems. The presence of onsite renewables could be integrated into the building's aesthetics to improve the overall look. It could be challenging to do for wind turbines.
- Flexibility: The integration of this source is dependent on the location of the building and, the availability of a renewable source. However, if it is congenial, it can be integrated easily with the installations, and they generally have low maintenance requirements. They can be integrated into new construction as well as for retrofit projects.
- Reliability: They have longer lifespans and relatively simple maintenance requirements ensuring the repair time is on the down low.

The use of renewable sources is contingent on the availability of infrastructure. In the case of onsite renewables, the feasibility is dependent on the location, and space availability denoting a lower degree of feasibility.

12. Use of low impact/biobased materials

Biobased materials are regenerative, have low impact, and theoretically, can be used endlessly. More information regarding the same can be referred to in the **5. Conceptual Model**. Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on ergonomics, costs, technical properties, physical properties, flexibility, and reliability.

- Ergonomics: The use of biobased materials for insulation and air distribution could contribute to a good indoor climate. However, any direct implication on ventilation and human health is still unclear and could be explored later in the future.
- Costs: The upfront costs for such materials could be higher considering their niche. The implications for costs for maintenance and operation are unclear and could be explored later in the future considering its limited implementation and awareness.
- Technical Properties: These materials have a very low carbon impact compared to primary materials. Its influence on energy consumption during operation, however, is still unclear.
- Physical Properties: Their area requirement could affect the entire building including the envelope. However, distribution networks employing such material have no comparable difference with those of conventional HVAC systems. An example is the Gatorduct discussed previously. The space requirement for primary equipment using biobased material is still unclear.
- Flexibility: Biobased products for insulation and ventilation ducts can be installed easily. However, as mentioned in passive design, insulation for walls can be installed easily during construction and could be cumbersome for existing buildings. However, the ease of installation of low-impact central equipment or release systems is still unclear. There is a possibility that it could be different due to the properties of such materials and increased complexity. Furthermore, the integration of such components with existing installations is also possible although compatibility and interoperability need to be investigated, especially for central equipment. Finally, for ease of maintenance, at least for air ducts, it is easy and just needs to be wiped intermittently. However, the maintenance strategy is still not standard and facility managers cannot guarantee the quality of the product post maintenance.
- Reliability: The lifespan for such materials is long and requires simple maintenance. For products on the market, the ease of maintenance ensures that any repairs are addressed quickly. However, the market is still nascent, so vendor availability is a concern.

Currently, there is limited innovation and availability in the market. Biobased air ducts are the only alternative solutions available commercially, demonstrating low feasibility in exercising this strategy holistically. Moreover, regulations currently do not yet accept many biobased alternatives as feasible.

13. Use of mono-materialistic components

Mono-materialistic components are designed using a single type of material which reduces the energy required for separation and recycling at the end of life. It also increases the potential for reuse without contamination and can be reintroduced into the production cycle through refurbishment/repurposing. Doing so allows for optimizing it for the technology cycle. However, it is critical to ensure that adopting this circular strategy does not compromise the effectiveness and performance of the equipment. It is pertinent that even mono-materialistic components can meet HVAC standards, temperature, and pressure requirements and ensure the health and well-being of occupants.

Given below is an analysis of how this circular strategy compares against evaluation criteria used for HVAC systems. It implies an effect on ergonomics, costs, technical properties, physical properties, flexibility, and reliability.

- Ergonomics: A well-designed system or equipment made of a single type of material has no direct implication on the thermal comfort of occupants.

- Costs: the upfront costs could be higher than conventional systems due to specialized manufacturing, limited production, and costs associated with innovation and research. The maintenance costs could also be higher since mono-materialistic components imply that organic solvents, lacquers, or paints are avoided and replaced with Cradle2Cradle alternatives that could be more expensive. Furthermore, considering the novelty, maintenance might require more specialized knowledge and expert technicians driving up maintenance costs.
- Technical Properties: While these components can improve the recycling potential and reduce embodied carbon associated with the recycling process, the implication on water, energy, or carbon emissions is not direct. there is potential to explore that aspect. As iterated above, the use of mono-materialistic components cannot compromise the performance of the equipment and should be able to generate and deliver conditioned air effectively.
- Physical Properties: The area requirements for such components/equipment could be different compared to conventional systems and they might require more area. The replacement of resins with more cradle2cradle-certified materials and resorting to the use of only one kind of metal could potentially change the appearance of these systems. It could align with a more "ecologically conscious" look if the entire building is constructed along the principles of circularity and sustainability.
- Flexibility: The implication of the use of mono-materialistic components in the installation process or integration with existing equipment is not known yet. However, manufacturing standardized equipment could ensure a standardized installation process and integration with equipment. The ease of maintenance might be compromised due to single material use. However, this can be offset by using alternative materials to prevent damage from exposure or corrosion. Another strategy could be having equipment behind demountable panels to ensure easy maintenance.
- Reliability: Proactive maintenance can ensure the longevity of the product. However, since it is not widely used and is a new concept, it is unclear if their lifespan is longer than conventional systems. Moreover, it does not fare well when it comes to the availability of manufacturers or spare parts. It could mean that if there are no spare parts available, the entire system would need to be replaced, which beats the entire purpose of using such components/equipment.

Currently, there are very limited options available commercially, and there is limited information about their performance which demonstrates a low level of feasibility.

The analysis conducted above represents a pivotal discovery in answering the main research question of this thesis. The outcome of comparing various circular strategies against a baseline scenario where no circular interventions are implemented unveiled how each strategy impacted these criteria. The outcomes not only elucidate the potential advantages and disadvantages of integrating circularity principles into HVAC systems but also provide valuable insights into the feasibility of implementing these strategies in practical applications. This analysis also revealed that while there were some direct implications and definite changes that can be recognized from these interventions, for some, the implications were still unclear, and that they can be explored further.

6.2 Validation of Findings

The final step of the iterative design process was to conduct an expert round as the last phase of the research methodology to assess the practicality and feasibility of the proposed product. After making modifications to circular strategies and articulating the implications of the proposed strategies, the expert round conducted included an elaborate discussion regarding the applicability and effectiveness of the proposed strategies. Following that, the expert was also asked to weigh in on the accuracy of the comparisons made by the researcher between HVAC systems with and without circular interventions. The expert constituting this round was a consultant with expertise in circular building installations. Their expertise offered specialized knowledge and insights into the latest technology, best practices, and a holistic perspective to identify how circular HVAC systems fit in the broader circular buildings context. They further provided meaningful recommendations and suggestions to improve the credibility of work. A summary of the discussion with the expert has been included in **APPENDIX D.**

6.3 Approach to integrating circularity in HVAC system design: A Decision Support Framework

This research focused on understanding circularity in HVAC systems by identifying applicable circular strategies, supported with relevant examples. Additionally, it assessed the practical feasibility, using an analytical approach and evaluating the impact on performance. The next crucial step is to structure these insights into a structured, practical approach that can be readily undertaken by MEP consultants when designing HVAC solutions for their clients.

Given below is a comprehensive, step-by-step guide that MEP Consultants can employ when they are approached by a client to design HVAC systems for a building. This guide is intended to be used during inception with a focus on creating circular building installations for HVAC systems.

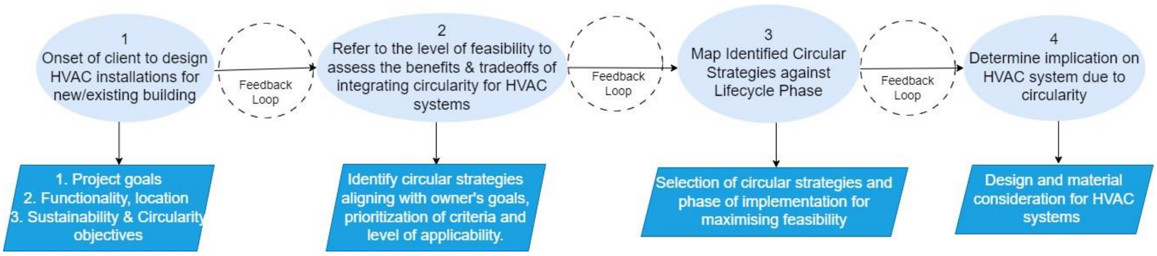

Figure 23: Systematic approach to apply circular principles to HVAC systems, a guide for MEP Consultants, own figure.

Given below is a concise description of each step, along with links providing access to figures and tables containing relevant findings necessary to complete that step.

1. Brainstorm with client to understand project goals, requirements, sustainability, and circularity objectives.

2. The process entails an iterative approach with the client wherein circular strategies are explored to align with the owner's criteria. This involves identifying potential interventions that best meet the client's prioritization of these criteria. To support the decision-making process, a comprehensive set of tables, structured as a matrix comparing circular HVAC systems with conventional systems against performance evaluation criteria can be consulted. These tables are arranged in the decreasing order of feasibility from A to C, enabling a clear understanding of the feasibility of each circular strategy and its associated benefits and trade-offs. As mentioned in **3.2.5 What are the Evaluation Criteria for HVAC Systems?** comparison against these criteria can help gauge what strategies can best meet the client's needs as the relative importance of each criterion is influenced by the owner's goals.

Prioritization of strategies according to feasibility was determined based on insights from interviews. This was to ensure the process was grounded in real-world considerations and reflected the practicality of implementing each strategy within the project context. This approach allows for the selection of appropriate circular strategies and guides considerations related to their lifecycle implications, utilizing the **Figure 21: Modified Lifecycle-Circular Strategy Mapping** for optimal impact and alignment with project objectives.

4. The last step identifies the practical implication of HVAC systems due to the selected circular strategies and the material and design considerations needed to integrate circularity to ultimately

design HVAC systems that are sustainable, circular, and deliver service efficiently. These implications can be referred to in **APPENDIX C.**

There are feedback loops to ensure alignment with project objectives, identify strategies that closely align with project requirements and owner's priorities, and engage effectively with the client. This is crucial to highlight the innovative aspects of circularity and communicate potential financial benefits. It emphasizes that clients rely on their consultants for knowledge and expertise. Moreover, evolving market conditions, regulatory guidelines, and technology advancements can influence the level of feasibility making feedback loops/iterations essential.

Table 5: Circular Strategies with High Feasibility (A)

		Performance Evaluation criteria					
Feasibility Category	Circular Strategy	Ergonomics	Costs	Technical Properties	Physical Properties	Flexibility	Reliability
A	Centralised Systems		Higher upfront costs but lower lifecycle costs	Lower water, and energy consumption but limited personalized control.	More space required, can affect aesthetic	More complex to install, more flexible to different energy sources, less flexible to evolving needs	Longer lifespan, longer repair time
A	Prefabricated Equipment		Higher upfront costs, lower maintenance costs	Lesser embodied carbon due to lighter structures, less waste	Lesser area requirement, better aesthetic	More flexibility overall	Longer lifespan, less repair time, good vendor availability
A	Product as a Service Model		Lower costs	Potentially higher efficiency		More flexibility overall	Longer lifespan, less repair time, less vendors
A	Repair/Maintain		Lower lifecycle costs	Reduces embodied carbon, emissions, potentially lower efficiency			Lower repair time, improve lifespan, and good vendor availability
A	BAS/BMS	Better indoor climate	Higher upfront costs and added maintenance costs, potentially lower lifecycle costs	Lower embodied carbon, reduced emissions, and energy consumption. More granular control.	Larger area requirement	More complex installation, better flexibility in case of new projects.	Longer lifespan, less repair time, good availability of vendors.
A	Flexible & Adaptable Design		Higher upfront costs. Potentially higher maintenance costs.	Potentially higher efficiency	Overdesign and futureproofing might require more material and space requirement	More flexibility overall	Longer lifespan, increasing vendor availability

		Performance Evaluation criteria					
Feasibility Category	Circular Strategy	Ergonomics	Costs	Technical Properties	Physical Properties	Flexibility	Reliability
B	Network Systems		Lower capital costs and overall lifecycle costs	Same as centralized systems.	Lesser space requirement but more distribution material	Lesser flexibility	More time for repair, longer lifespan
B	Sharing Spaces	Can achieve ideal indoor climate with BMS	Higher upfront costs but lower lifecycle costs	Lower emissions and energy consumption		More flexibility overall	Longer lifespan, longer repair time
B	Product as a Service Model		Lower costs	Potentially higher efficiency		More flexibility overall	Longer lifespan, less repair time, less vendors
B	Use of Renewable Sources		Higher upfront costs for on-site renewables. Lower lifecycle costs	Lesser environmental footprint	On-site renewables require more space, can improve aesthetic	Easy to integrate, low maintenance.	Longer lifespan, lower repair time
B	Utilising Reusable/Refurbished Equipment		Higher upfront costs, potentially higher maintenance, and lifecycle costs	Reduces embodied carbon, emissions, potentially lower efficiency	Could conform to aesthetic of sustainable building	Less flexible and risk of incompatibility	Lesser reliability

Table 6: Circular strategies with medium feasibility (B)

Table 7: Circular strategies with low feasibility (C)

		Performance Evaluation criteria					
Feasibility Category	Circular Strategy	Ergonomics	Costs	Technical Properties	Physical Properties	Flexibility	Reliability
C	Passive Design	Comparable comfort but inconsistent in temperature, humidity control	More upfront costs but lower lifecycle costs	Lesser water, energy consumption and emissions but limited precision	Lesser space requirement, improves aesthetic	More complex, lesser flexibility but easier to maintain	Longer life but less vendor availability
C	Mono-materialistic components		Higher upfront costs, and maintenance costs	Risk of not meeting specifications for temp/pressure	Could conform to aesthetic of sustainable building.		Lesser reliability
C	Use of biobased materials		Higher upfront costs.	Lower carbon footprint	Area requirement for distribution comparable to conventional systems. could conform to aesthetic of sustainable building	Easy to maintain and install for distribution	Long lifespan, low vendor availability.

7. Discussion

This chapter outlines the main takeaways and reflection of the findings from the **6. DATA ANALYSIS AND RESULTS.**

7.1 Practicality of the Decision Support Framework

To revisit the motivation of the research, it was to understand the slow adoption of circularity in the services layer of the building. To recognize the practicality of the proposed guideline mentioned in **6.3 APPROACH TO INTEGRATING CIRCULARITY IN HVAC SYSTEM DESIGN: A DECISION SUPPORT FRAMEWORK**, it is essential to understand why traction has been low. Stakeholder sentiment within the building's supply chain network, especially in the context of HVAC systems, plays a crucial role. The consensus highlights uncertainties and apprehensions surrounding circularity's success, an evolving concept. The lack of a standard definition highlights its uniqueness.

These challenges extend to circularity for HVAC systems. Most of the stakeholders are unsure of how it operates and its efficacy. The significant investment required, both monetary and knowledge, just reinforces their apprehension. The guideline encompasses both conventional and innovative strategies that emphasize the tangible impact on existing systems. The inclusion of "conventional" practices potentially reduces the sense of uncertainty and hesitation to implement this concept in practice and provides a clear path to foray into this concept. Moreover, repositioning these "conventional" practices like use of centralized systems, repair, using BMS/BAS under the "circularity paradigm" can help alleviate the industry's knowledge gap regarding circularity. This strategic repositioning not only helps them achieve their sustainability goals but also makes it more approachable for stakeholders who may lack familiarity with the concept.

The study also uncovered a hindrance to circularity integration - a cycle of blame where stakeholders await others to act first. The market waits for the government or regulatory agencies to disclose more information or more thorough guidelines. To break this impasse, government and regulatory bodies need to take the lead which can serve as catalyst for the technical services industry. As exemplified by recent initiatives in 2023, The European Commission adopted a new corporate sustainability reporting directive that requires full company disclosure to their resource use and circular economy performance by 2025 (Verstraeten-Jochemsen, 2023). However, this also requires companies to prepare for disclosure by 2023 by identifying circular economy related risks, opportunities, develop strategies and performance which can be a complex process. The developed guideline highlights a comprehensive list of strategies tailored to HVAC system which also includes their benefits and trade-offs. Moreover, it establishes clear evaluation criteria which can be used to assess circularity performance for HVAC systems. Hence, it offers an initial assessment tool to help companies devise strategies and the circular HVAC system performance matrix serves as a performance monitor. While quantification and expansion of these criteria would enhance its effectiveness to measure circularity performance, even in its current form, it acts as a starting point to prepare for impending regulatory initiatives.

The market also exhibits this cycle of hesitation wherein stakeholders often wait for proof of success and its feasibility before applying it. A major driver of this resistance is due to the evolving, complex nature of the concept, significant financial investment, and the lack of regulatory affirmation. The waiting game persists due to lack of awareness, evident in findings where market parties are uncertain about actionable steps, they can undertake to drive the transition. Also, their familiarity with the tried and tested methods and mistrust invokes stagnation. Although, most of the interviewees do reveal that there is a need to transcend this cycle. An intrinsic sense of environmental consciousness, and responsibility towards society can break the cycle. The developed guideline includes the level of feasibility for the identified strategies along with practical implications on HVAC systems based on availability in the market and interviews with stakeholders from the industry. This can build confidence in circularity by transforming abstract ideas into actionable strategies and positioning them to adapt and incorporate circularity. Also, the research does identify roles and responsibilities for market parties to undertake to plant a seed of thought and break the cycle of blame and inaction.

A stark observation made by the researcher was the conflation of sustainability and circularity. Circularity is a component of sustainability, rather means to an end. One could be sustainable by adopting renewable sources as their primary source of energy to power the installations but there are other markers to sustainability as well. Continued reliance on resource heavy HVAC installations just because it is being powered by renewable energy is a misinterpretation of the principles of circularity. Although a step forward, it is important to realize that circularity also necessitates reduced consumption of resources. By prescribing the ways to incorporate circularity, the framework can help deliberate what it means to become circular for HVAC systems and resolve this misinterpretation.

7.2 Reflecting on Circular Strategies Performance and Feasibility

The guideline identified that the use of reusable/refurbished equipment does not impact thermal comfort. Recognizing this can drive efforts to retain as much efficiency and quality as possible through better maintenance and designing for longevity. Awareness of such equipment and its impact can help reorient supply and demand to favor their adoption. However, the researcher does realize the risk of incompatibility of used equipment and ways to mitigate that risk can be explored further. Manufacturing companies and suppliers could explore developing "retrofit packages" that could enhance the performance of equipment and allow integration with newer equipment through control systems or energy efficient components etc.

Another aspect that merits further consideration is the performance gap, wherein older equipment may exhibit reduced efficiency and higher energy consumption. To address this concern, future work could incorporate carbon lifecycle assessments like **3.7 Frameworks and Indicators for Carbon** to find the optimum balance between reducing emissions and reducing embodied carbon.

Furthermore, the matrix acknowledges the pivotal role of maintenance history, condition, and performance in determining the feasibility of reusing older equipment. However, regulatory enforcement requiring reliability certificates from marketplaces and manufacturers along with material passports can bridge the information gap. The assessment of reused/refurbished equipment as less feasible acknowledges the nuances of this strategy. However, the stakeholders also revealed that several equipment including AHUs, Heat pumps, heat exchangers, pipe networks, ducts, refrigerants, and terminal units like radiators can be reused if treated for mold, contaminants, corrosion, and replacement of moving parts. This highlights that equipment can be reused albeit after replacement of few components to retain efficiency.

Another introspection is regarding flexible and adaptable systems. Repurposing flexible systems for other buildings or during refurbishment projects is possible provided there is a standardization of space layouts. Achieving this standardization could be challenging but is key to maximizing the impact of the systems. However, the use of standardized, modular equipment and installing demountable equipment is highly feasible. Although, the upfront costs could be higher, designers and manufacturers are opting for these practices to meet evolving demands both due to climate change and adapt to changing levels of occupancy with hybrid working conditions, a dominant practice post COVID.

Additionally, it is identified that while passive design can reduce the need for mechanical ventilation, its total replacement is not happening anytime soon. The lack of optimum temperature and humidity levels do not align with the performance requirements to be met for buildings. However, if not all, some passive features like optimizing daylight through windows, glazing, shading systems, Trombe walls can be incorporated to reduce air-conditioning demand.

This also reflects not only on the stringent code and compliance requirements set by regulatory bodies but also lack of dynamic thinking by stakeholders. There is a need to question whether all the rooms need air conditioning, do we need to always supply air at the same rate and can we design a building that offers holistic thermal comfort on its own. It resonates with what an MEP consultant remarked, “The buildings are too tight which is why we cannot do without HVAC” or what an architect said, “We have not considered passive design.” Highlighting the comparable level of comfort, low impact, positive effect on health and wellbeing, and long life of passive design can incentivize designers and other stakeholders to incorporate this practice.

Reflecting on the use of biobased materials or mono-materialistic components, the researcher encountered limitations in exploring their relationship with performance criteria. This limitation arises from the nascent stage of these materials, prompting the potential for further investigation as the market and innovation evolves. An intriguing perspective emerged during one of the interviews, wherein, manufacturing ducts from recycled textiles or other low-impact repurposed/remanufactured products represents a “hobbyist” approach as it is also energy intensive. However, with the little innovation made albeit only for air ducts in HVAC systems, the initiative does lower carbon footprint and can contribute to sustainability goals. It functions as a closed loop system, which is generally a better alternative to using virgin materials.

To conclude, while the performance evaluation criteria does offer valuable insights, they present limitations in fully capturing circularity’s impact on HVAC systems. Although, the level of feasibility identified for each strategy does consider their nuances and level of applicability, future work could focus on expanding the criteria for a more comprehensive assessment of circularity, addressing resource efficiency, longevity, and adaptability.

7.3 Contribution made to existing literature.

While the existing literature includes abundant information about the various circular principles and ways to exact them, this research has aimed to offer a starting point to adapt circularity for HVAC systems. The examples mentioned in **5.2 CIRCULAR STRATEGIES** are specific to HVAC. However, the categorization of strategies in the loops of circularity they cater to offer consultants with a simplified approach to take to conform to for each loop. Moreover, this study has aimed to break down CE, into smaller, actionable strategies clustered by their feasibility which can help alleviate the feeling of overwhelm associated with this complex concept. This research also touches upon the ways to reduce reliance on HVAC systems by comparing passive design strategies against the performance criteria used to evaluate HVAC systems.

Furthermore, the study consolidates information about the most used HVAC systems and relatively unconventional alternatives which can aid consultants in choosing HVAC systems with due consideration for materials and resources required. As mentioned before, the concept is relatively new and there is a lot of evolution underway, so this research contributes to the addition of knowledge and assists the stakeholders with a guiding framework.

7.4 Gap in Theory vs Practice

7.4.1 Collaboration

The interviews revealed similar requirements for collaboration, expansion to existing roles and new roles as identified in literature. Most of the participants agreed that the design process requires more stakeholders owing to its complexity. However, there was a lack of consensus observed about the early involvement of the contractor. While literature advocates it, the industry had contradictory observations. The practitioners believe that contractors' probable reluctance to try innovative methods and their profit driven mindset might be counterproductive. They believe contractors should be involved in the design process for their expertise in materials and the market but not given the lead. Differing agendas and opinions could imply delays in the design phase. Lastly, while literature and interviews stress the need for early manufacturer involvement to access innovation and expertise they often interact primarily with contractors. Collaborating with the entire project team, from research to installation, may be time consuming and affect effective early involvement.

7.4.2 Overdesigning as a strategy for Flexibility

Overdesigning was recommended as a strategy by a few participants to meet future demands and modifications. However, as observed in **3.2.6 Issues prevalent in current HVAC Systems and their Lifecycle Process and potential link with Circularity,** overdesigning contributes to more emissions, embodied carbon and higher upfront and running costs. Literature states that overdesigning as a problem can be mitigated by upgrading and installing newer, bigger systems as and when the need arises. Another alternative recommended is modular design comprising many smaller units which can collectively meet peak requirements, offer flexibility or a one size modular formation that utilizes different size units for more agility (Jones, 2019). However, unit duplication is contradictory to resource minimization. Future work could focus on finding an optimum balance between minimizing resource consumption and minimizing operational carbon 3.7 Frameworks and Indicators for Carbon).

7.5 Implication of Circular Strategies on Factors affecting system selection

As elaborated throughout the course of research, the feasibility of applying circularity is highest when done in the initial stages of the project, which ties in with the decision-making process. This section focuses on the criteria mentioned in **3.2.2 Selection of an HVAC System.** The researcher has elaborated on the criteria that did not overlap with performance evaluation criteria since that has been discussed at length in **6.1.4 Comparison of Circular Strategies against HVAC Evaluation Criteria.**

7.5.1 Design, orientation, and location of building

Throughout this research, it is evident that a building's orientation, location, and design of the building determines its reliance on HVAC systems. This requires a multi-disciplinary effort from all the stakeholders and alignment in their priorities. Circular and sustainable objectives must hold equal weight with considerations of thermal comfort and aesthetics. This can be inferred from an interviewee's preference for glass facades and open layouts to enhance thermal comfort and aesthetics emphasizing that orientation cannot solely hinge on energy use. The matrix shows trade-offs to be made. It reflects on a crucial thought; you may not have it all. Therefore, achieving thermal comfort, acoustics, material efficiency, and energy efficiency collectively is unlikely. It requires dynamic thinking and redefine standards associated with these characteristics. While it could be a comprehendible feat to achieve in the future, there is more to be done. This requires more time for iterations/feedback loops to understand the system and the value chain. A way to incorporate rethink of how building design can be leveraged for reduced need for HVAC is by scheduling more time in the initial stages for "research". This explores the feasibility of such practices and developing ambitions that prioritize passive design.

7.5.2 Owner's choice

The owner can be one of the biggest catalysts to bring circularity in HVAC systems. Their enthusiasm and drive to be more sustainable will reflect in the ambitions of the project and determine the team they assemble to exact that ambition. As mentioned before, if the client has a strong foresight about the future lifecycles of the building, it translates into flexible design and consequently flexible HVAC systems. Furthermore, a major onus is also on their advisors and the design team as the client relies a lot on their knowledge and expertise. So, it is pertinent that they inform them and even convince the client to make decisions that favor circularity and sustainability. Persuasion is often necessary because of the significant financial investment and uncertainty on returns. So, consultants bear a huge responsibility of educating the client about the benefits of their investment, because circular design relies on both physical design and the business model.

7.5.3 Building codes/regulations

Finally, building codes and regulations that are established by municipal or other governing bodies probably have one of the biggest roles to play in accelerating the transition to circularity for HVAC systems. To begin with, they need to reevaluate the standards and compliances that have been set. Interviewee 8 stated, *"Do we even need such strict regulations for maintaining thermal comfort for utility buildings"?* Building codes mandate the installation of HVAC systems for office buildings that contain a certain number of occupants. It is vital to actively consider including passive design features as a regulation.

Moreover, building codes also require certain parts of HVAC systems to be replaced and cannot be used beyond a certain period. This is applicable even for the use of biobased/alternative materials that are not accepted as reliable and hygienic yet, according to standards. For instance, for fire safety, and acoustics, the implications are different when biobased materials are used as opposed to conventional materials. That does not necessarily mean they are not functional but that the benchmarks need to be recalibrated.

8. Conclusion and Recommendations

This research aimed to address the existing gap in circularity within building services, particularly for HVAC systems in utility buildings. Results from this research recognize the potential impact of circular interventions on these systems. By comparing them against conventional systems using evaluation criteria employed to assess their performance and recognizing their feasibility, this research identified opportunities and highlighted measures to curtail reliance on mechanical solutions. This research was steered by the main question, "How can circular strategies influence current HVAC systems for utility buildings?".

To answer the same, a literature review was conducted followed by semi structured interviews from stakeholders of the industry and supply chain network. Consequently, experts from the field of circularity and installations for the buildings were consulted for validation. Thematic analysis was undertaken to decipher findings from the interviews.

A few sub research questions were developed to aid the investigation and each chapter of this report contained insights corresponding to these sub research questions. Findings from each chapter have been aggregated and developed to answer these questions and are elucidated below.

SQ1: What is circular economy and what frameworks are currently being used to implement it in the built environment?

The built environment's resource consumption and emissions, encompassing both operations and embodied carbon demand immediate attention. Resource efficiency, waste minimization, and reduced dependence on primary materials is imperative. This requires a paradigm shift involving development of new business models, modification of components, systems, and rethinking design processes. Circular economy seeks to achieve that and create a regenerative system while safeguarding natural resources. The flexibility of this concept renders it applicable to many regimes, material, component, product and even municipality or city levels. The first section of the literature review aims to encapsulate the core principles of circular economy, highlight its significance in the built environment and showcase how it translates to flexible buildings. It also surveys prevailing industry practices pertinent to this research. The strategies identified are not exhaustive but distilled for a comprehensive yet concise representation for more relatability and practicality. This approach ensured effective communication during interviews.

SQ2: What are the various components and systems encompassing HVAC systems for utility buildings and what is the current level of implementation of circularity in them?

The second segment of the literature review discussed HVAC systems for utility building, comprising both complex equipment and systems. The investigation aimed to comprehend the present state of installations' sustainability and potential for circular interventions, involving both conventional and emerging technology. Important characteristics like their material composition, lifespan, complexity of installation and their method of installation were investigated to ascertain circularity needs. This established a foundation for identifying circular strategies' potential impact. Moreover, recognizing performance evaluation criteria enabled a comparison between circular HVAC strategies and conventional systems.

This section also uncovered circular initiatives led by the industry such as products as a service model for pumps and air conditioning, and use of biobased materials for air ducts. These success stories reveal potential for circular interventions. Nevertheless, this research emphasized addressing circularity's limited traction within this building layer and describing the need to propel its adoption.

SQ3: What kind of stakeholders are involved for HVAC systems in utility buildings and what role can they play in transition towards circularity?

The concluding section of the literature review conducted an analysis of the stakeholders within the supply chain network and the lifecycle of building HVAC systems. Given the qualitative nature of this exploratory research, identifying influential stakeholders was crucial to aid the transition. This analysis aimed to bridge the theory and practice, offer insight into their perspectives, perception regarding circular interventions' practicality for HVAC systems and requisites to further the concept in their capacity. Circular concepts require interdisciplinary collaboration and holistic thinking, exemplifying the significance of recognizing involved actors. Interviews with the stakeholders discovered their shared requirement for knowledge about alternatives to current systems, modification, and corresponding implications. Notably, a more concrete regulatory framework emerged as a prevailing requirement. In summary, all the stakeholders acknowledged substantial circular potential. However, they attributed industry reluctance to unfamiliarity and await government or regulatory enforcement for action.

SQ4: What are the barriers and opportunities for integrating circularity for HVAC systems?

The conclusive element required to formulate recommendations and a practical framework lay in discovering industry challenges and incentives or developments required for adoption. The literature review provided actionable insights, but the interviews revealed how practical and feasible they were in the industry. This knowledge was pivotal in identifying ramifications of circular strategies for HVAC systems and learn about potential benefits and trade-offs. Furthermore, these interviews revealed opportunities aligning with industry led practices and augmented the decision support framework. This sub question was fundamental in drawing comparison between circular HVAC systems and conventional ones which allowed for a holistic guideline that informs decision makers of not only ways to apply circular strategies but also their level of feasibility and practical implications for HVAC Systems.

8.1 Answering the Main Research Question

The researcher's primary objective was to explore integration of circularity within HVAC systems and elucidate its implications. Circular strategies were explained through HVAC relevant examples. The conscious approach of structuring a phased circularity integration comprising a select set of strategies aimed to avoid overwhelming stakeholders and offer an initial glimpse into circularity's potential impact and offers clients and consultants with a practical starting point. Categorizing them by feasibility conveys a systematic understanding of circular economy. Moreover, it may reduce the potential for time and cost overruns, a common risk associated with novel concepts like circularity. If there is a limited set of strategies, clients also gain a clear understanding of what falls within the project's scope, leading to fewer iterations and significant changes.

Moreover, the comparison of circular HVAC systems against conventional systems by recognizing their influence on the criteria renders it easy to refer to for the advisors/consultants. While quantification and a definite timeline for the level of feasibility identified could enhance the comparison made, this avenue remains available for future exploration. Additionally, it provides a more actionable roadmap for consultants and clients who seek to incorporate circularity in HVAC design and ensure that strategies selected for adoption are realistic to exact.

A pivotal outcome of the decision support framework was to address the challenge of assessing circularity. Aligning the strategies with circularity loops revealed their potential degrees of circularity ranging from resource to material efficiency. Furthermore, it also facilitated early-stage environmental impact estimation, helping conceptual design when multiple options are under consideration.

The framework's interpretability makes it versatile and applicable even when the client already possesses a clear ambition of circularity and specific principles they wish to incorporate in their project. For instance, if a client's priority is product life extension, the focus could be on strategies within the 'slowing' category and assessing its performance to conventional systems in the matrix. This interpretability empowers the client to select strategies that best match their criteria and ambition, ensuring an informed and customized decision-making process.

Essentially, the MEP consultant is now presented with alternatives to conventional HVAC systems and is apprised of their consequences. They can advise a client of choices for circular interventions and what they entail. However, much depends on the client's ambition and when they communicate it to their advisors. Early involvement is crucial because many strategies require consideration from the project's outset and become more challenging to implement if the ambition is realized later in the process. Hence, although this report is intended for consultants, it can also be helpful for clients in discovering the possibilities for circular installations, realize why is it needed and incentivize them to invest in such practices. It is important to acknowledge that the practice of these strategies does require willingness to learn and adopt newer roles and functions by both the consultant and the client. Furthermore, this report also includes practical implications for HVAC systems and actionable insights for other stakeholders which can drive up demand for circular solutions.

This research helps illustrate the need for circularity for HVAC systems and advocates for a shift towards more sustainable systems. It prompts a critical examination of increasing reliance on such systems and introspect their need. While it does not offer definitive implications of integrating circularity, it informs us of the possible influences and encourages consultants to consider these alternatives.

8.2 Limitations of Research

This section acknowledges and discusses the limitations of the research conducted. Recognition of these constraints offers insight into potential areas for future research and are mentioned below.

Primarily, the scope of the study was confined to the design, construction, and maintenance phases of HVAC systems overlooking broader aspects like metal extraction, supply chain, logistics, i.e., the material flow. This limitation potentially overlooks a comprehensive life cycle understanding, excluding vital insights into resource consumption, emissions, and environmental impact in a broader context.

Another limitation due to scope was that the research did not fully address the potential impact of energy grid and the existing infrastructure on the implementation of circular HVAC systems. This can significantly influence the feasibility and performance of HVAC strategies, especially those involving renewable sources and district heating. Although the impact matrix acknowledges this interaction, future research could offer a more holistic understanding of the interplay between circular HVAC systems and energy infrastructure. Moreover, the researcher tweaked the guideline to incorporate level of feasibility based on brainstorming with supervisors and recommendation from the expert. However, that aspect of the guideline was not validated further due to time constraints and can be explored further.

Based on the research methodology, a limitation is observed. The researcher could not conduct case studies due to time constraints, rendering the framework theoretical. While validated by industry experts, the theoretical nature requires the need for further research to practically test the framework's applicability, effectiveness, and feasibility. Real-world application and success of circular HVAC strategies may deviate from theoretical analysis.

Another limitation stems from the limited rounds of interviews conducted which could limit the depth and diversity of perspectives garnered. This suggests that some nuances, challenges or more opportunities could be left unexplored and not fully represent the range of stakeholders' views potentially influencing the accuracy and interpretation of conclusions.

Furthermore, the qualitative and exploratory nature of the research implies that the findings are grounded in interpretations and perceptions, potentially introducing bias from both the interviewees and the researcher. Moreover, the analysis of the circular strategies of its relation to the performance evaluation criteria hinges on the researcher's interpretation of literature and interviews which could imply deductive reasoning. It recognizes the possibility that new information or perspectives could influence the relationship established. So, this research only initiates the first step as exploratory research that shows how circularity influences HVAC systems offering a foundation open to evolution and interpretation by various stakeholders. This aligns with the evolutionary nature of circular economy as well. With more innovation and changing guidelines, the relationship might be subject to change.

In conclusion, the research does offer valuable insights into the potential of circularity for HVAC systems, but these shortcomings underline the need for continued efforts in exploration, validation, and development of work to achieve a more robust and nuanced understanding of circular practices in this industry.

8.3 Recommendations for Practice

- It is recommended that Dutch regulatory bodies revisit building codes to incorporate passive design principles into utility buildings. BENG urges employing passive design for residential homes, it can be done for utility buildings as well. Mandating inclusion of passive design in building codes along with defined performance standards would ensure tangible outcomes. A mixed mode strategy will alleviate the climate impact and reduce resource consumption. Collaborating with experts to provide guidance and training for implementation would further streamline the adoption of these principles.

- A recommendation is to consider the possibility of long-term partnerships spanning many years between the consultant/architects and client to make the design team a part of the network such that they can follow and evaluate the lifecycle of their designed product/buildings. This stimulates engagement even after the design is finished and they are more invested in pushing for circularity. Exploring revenue models that reflect on circularity as a process and not a time bound contract can incite more involvement of these stakeholders. This can also help counteract the hesitation of client with respect to added upfront costs of circularity. A long-term partnership can allow gradual increment in applying circular principles to lower the initial investment and adapt the building to meet evolving needs. The feasibility levels also allow them to progress incrementally and adapt to changing regulations and advancements in technology.
- The need for collaboration and partnerships can also be extended to manufacturers and suppliers who can combine forces as competitors to innovate and develop products/solutions that are long-lasting, use alternative materials, and discover newer ways to incorporate circular thinking. Reimagining secondary marketplaces/urban mining companies as future material providers can require consultants and contractors to establish a network with them. Currently, there is little awareness about their presence and body of work. Awareness through webinars, workshops, exhibitions, or even social media platforms can inform the supply chain network.
- The research successfully mapped circular HVAC against existing performance criteria. However, to comprehensively encompass circularity's impact on HVAC, the researcher recognizes additional criteria. Expanding the assessment to incorporate metrics like percentage of reusable material, ease of disassembly, potential for component recycling, adaptability to evolving technology and extended product life can provide a more informed evaluation of circularity within HVAC systems.

8.4 Recommendations for Future Research

This research produced significant findings conforming to the scope of the research of circularity can be applied to HVAC systems and rendered significant information both about circular economy and HVAC systems. Findings from the current study postulate multiple avenues for future research that can further enrich understanding of circularity in HVAC system and its broader implications that have been elaborated below.

- Feedback acquired from expert validation yielded insightful suggestions that could refine the accuracy and comprehensiveness of the framework. Future studies could focus on incorporating the feedback given and working on the recommendations provided. Exploring the relationship between these two bodies of work would enhance the foundation of circularity's influence on HVAC systems.
- Exercising the framework on actual projects could yield interesting results and observations that can improve the practical application and suggest modifications aligned with industry practices. This could be done through case studies by investigating how do HVAC systems with circular interventions perform in comparison to conventional systems.
- This research was qualitative in nature and explored the relationship between circular interventions and performance evaluation criteria. A significant direction of research could be quantifying the relationship, potentially monetizing the impact of these interventions. Monetization equips decision makers with tangible metrics to evaluate the cost-benefit of

circular HVAC strategies, aiding long-term resilience and sustainability. Another aspect could also be linking it KPIs like the Material Circularity Indicator (MCI), Environmental Cost Indicator (ECI) to quantify the impact of these circular strategies by applying it to cases/projects.

- While this research identified new roles and functions for stakeholders, future studies could focus on identifying collaborative approaches and leadership styles to identify ways to implement circularity for services in buildings. Since it is all new territory for the market and its stakeholders, they must forge new ways of working together and the added responsibilities would require exploration of synergies, conflicts, and partnerships. All the stakeholders agreed that they need to work together right from the beginning, but it is challenging to do so with many opinions and differing priorities. Future work could focus on studying cases and identifying the roles, level of involvement for each stakeholder considering project specificity. The researcher realizes that this is an important avenue that could be studied in future.
- The researcher strongly believes that future research could investigate the policy and building code landscape relevant to circular building services systems. examining how government regulations and industry standards can be adapted or developed to incentivize circular strategies could offer insights into the institutional instruments required to scale circularity for HVAC systems. While this research does touch upon the regulatory changes that are required to initiate widespread adoption, conducting an in-depth study on this can yield interesting recommendations. This research discovered interesting takes for the government to potentially enforce, from interviews with stakeholders, an in-depth study can offer compelling recommendations and constructive means for policy reform through efforts at various levels.
- Finally, future work could focus on identifying additional criteria to comprehensively encompass circularity’s impact on HVAC. Expanding the assessment to incorporate metrics like percentage of reusable material, ease of disassembly, potential for component recycling, adaptability to evolving technology and extended product life can provide a more informed evaluation of circularity within HVAC systems.

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Appendix A- Interview Guide

Introduction:

- Name of the researcher
- Educational Qualification
- Current academic endeavour
- Research objective
- Purpose of interview
- Informed consent/ confidentiality clause

Context

- Description of company's function, sector, position in the market
- Qualification of the interviewee
- What is your role and for how long have you been working here?
- What are the goals of the company concerning 2030 and 2050 targets set by the EU and NL?
- What are the goals of your organisation regarding circular economy in your products and services?
- **Theme 1**: General Questions
- **Theme 2:** Circular Economy in Built Environment
- **Theme 3:** Circularity in HVAC Systems
- **Theme 4:** Measures to implement this and determine what is required to facilitate the implementation.
- **Closing Remarks**
- Expression of appreciation for the interviewee's time (Baumbusch, 2010).
- Any final thoughts or reflection that could help the researcher amend the guide (Magaldi, 2020).
- Discuss the plausibility of reviewing the transcript at the interviewee's discretion.

Questions for Building Owners/Clients

Theme 1: General Questions

1. What kind of stakeholders are you directly involved with (contractor, architect, EOL parties)?
2. How is the decision-making process like when you decide building design, layout, building components?
3. How important is collaboration with stakeholders for you and why?
4. Do you think there are issues with collaboration and transparency?
5. How involved are you with the sub-contractors- HVAC contractor?
6. What are your priorities or objectives that you wish to achieve in a project?
7. In which stage of the project were the contractors and sub-contractors hired?
8. What is the method of procurement and what aspects are considered when choosing a manufacturer and a contractor?

9. What are your criteria when deciding an HVAC system for the building?

Theme 2: Circularity

1. How aware are you about circular economy?
2. Have you ever been a part of a project or an initiative before that involved circular practices?
3. why do you think, circularity has not received as much traction as it needs to, considering the 2050 and 2030 goals?
4. What is your opinion on buying used components to prolong the life and reduce waste?
5. what is your opinion on switching to product as a service model?
6. what do you think about future proofing and flexibility in spaces at the cost of a finished look?
7. what is your preference; sourcing products from different manufacturers, or systems from one manufacturer.
8. what do you think about the practicality of the 10R framework or the ReSOLVE Framework?
9. How helpful do you think are tools like Material Passports and BIM?
10. How inclined would you be to invest in such solutions?
11. how much potential do you think these tools have in promoting circularity?
12. how inclined would you be to collaborate with secondary market owners early on to buy or sell used products?

Theme 3: Circularity in HVAC Systems

1. Do you feel the building installations segment of a building is further behind the other aspects of a building in terms of circularity?
2. What do you think are the reasons for lack of circular initiatives in this domain?
3. Are you aware of circular initiatives already in place for HVAC Systems?
4. Do you have a say about what happens to the HVAC systems/components at the end of life?
5. How are they being disposed currently?
6. What do you think are the risks associated with the implementation of circularity principles for HVAC systems?

Theme 4: Circularity measures and requirements

1. Do you think receiving subsidies or tax exemption or benefits from the government will help push this agenda?
2. Do you feel that policies in place might aid the cause?
3. What information or expertise do you think we need to implement circularity in HVAC installations?
4. What do you think about the effect of early involvement of contractors, manufacturers, and end-of-life parties on circularity implementation?
5. What other forms of collaboration (maybe with other firms) would you think would help this initiative?

Questions for Consultancies

Theme 1: General Questions

1. What are the range of services you offer wrt HVAC systems for buildings?
2. How do you collaborate with the architects/design team of the client and the client?
3. How do you choose an HVAC system and what are the criteria for selection?
4. How do you collaborate with the contractor and the manufacturer?
5. How involved are you in the later stages of the project i.e., the end-of-life phase?
6. How do you choose a manufacturer?

Theme 2: Circularity

1. How well do you know the concept of CE?
2. why do you think, circularity has not received as much traction as it needs to, considering the 2050 and 2030 goals?
3. Have you ever been a part of a project or an initiative before that involved circular practices?
4. How do you convince clients to invest in circular solutions?
5. What are the apprehensions on recommending to buying used components to prolong the life and reduce waste?
6. what are your apprehensions towards recommending switching to product as a service model?
7. What is your advice on procuring products from different manufacturers vs systems from one?

Theme 3: Circularity in HVAC systems

1. Why do you think the building installations segment is lagging in CE?
2. What efforts have you taken to include circularity for HVAC systems?
3. Do you consider the material composition of the components and products that comprise a HVAC system?
4. Can HVAC systems also be designed to be deconstructed much like other layers of the building?
5. Do you think rethinking the requirement of HVAC services for a certain space can reduce the need for it at all? (Re-think)
6. Do you think lack of standardisation of products and missing information can affect the transition?
7. Can the plug and play concept also be implemented for HVAC systems?
8. Can passive design strategies replace the need for HVAC systems?
9. What will be the impact of reimagining the functionality of buildings on circularity in HVAC systems?
10. What is the likelihood of biobased materials replacing the conventional materials being used for HVAC?
11. What is the likelihood of using mono material components or components that can be easily recycled?
12. Is there a possibility to share assets to reduce resource consumption?

13. What steps can be taken to design out waste during manufacturing or production or construction?
14. What is the impact of using reusable/recycled components on costs?
15. Do you think predictive maintenance, monitoring can increase lifespan?
16. What steps can be taken to reduce the rate of replacement of HVAC systems?
17. What do you think of the ROI of using circular hvac systems?
18. Are components often replaced despite having potential?
19. What are the implications of using used products or components?
20. What are the risks of adopting CE for HVAC systems?

Theme 4: Circularity measures and requirements

1. What information or expertise do you think we need to implement circularity in HVAC installations?
2. What is required to DFD?
3. What can be changed or done in other layers of the building to reduce the need for HVAC systems?
4. Can there be other uses for old components of hvac systems?
5. What do you think about the effect of early involvement of contractors, manufacturers, and end-of-life parties on circularity implementation?
6. What do you think of your early involvement during initial concept with the client?
7. What other forms of collaboration (maybe with other firms) would you think would help this initiative?

Questions for Architects

Theme 1: General Questions

1. How do you collaborate with clients, MEP consultancies and the contractor?
2. Are there issues with respect to information transfer, transparency, collaboration in this process?
3. How involved are you when it comes to the design and selection of HVAC systems for a building?
4. How involved are you in the later stages of the project?
5. What are the criteria you follow during design of a building?
6. How do you think it impacts the choice of an HVAC system?

Theme 2: Circularity

1. Are you aware about the concept of circular economy?
2. Have you been involved in the design of buildings that conform to the principles of circular economy?
3. How do you convince clients to invest in circular solutions?
4. What do you think are the issues wrt circularity inclusion in the built environment?
5. What are the apprehensions on recommending to buying used components to prolong the life and reduce waste?

6. what are your apprehensions towards recommending switching to product as a service model?
7. what do you think about the practicality of the 10R framework ?
8. How do you think these tools can promote circularity?

Theme 3: Circularity in HVAC systems and integration

1. Do you have a say in the material selection for the components and products that comprise an HVAC system?
2. What do you have to say about standardisation of products and components of an HVAC system?
3. Do you think design methods like design for deconstruction can be implemented even for HVAC systems where they can be taken apart easily and be more modular?
4. How do you think the design of the building including the space layout, ceilings, flooring, facades, windows, doors can be made compatible with DfD HVAC systems?
5. Do you think early involvement of the HVAC contractor is good for CE adoption?
6. Why do you think circularity is lagging in building installations?
7. What issues do you think exist in terms of collaboration that delay circular transition for hvac systems?
8. What is your opinion on working with the manufacturer and the contractor in the design phase?
9. How can your involvement in the end-of-life stages help with circularity in HVAC Systems?

Theme 4: Circularity measures and requirements

1. Do you think receiving subsidies or tax exemption or benefits from the government will help push this agenda?
2. Do you feel that policies in place might aid the cause?
3. What information or expertise do you think we need to implement circularity in HVAC installations?
4. What do you think about the effect of early involvement of contractors, manufacturers, and end-of-life parties on circularity implementation?
5. What other forms of collaboration (maybe with other firms) would you think would help this initiative?

Questions for Manufacturers

Theme 1: General Questions

1. What kind of products and components do you manufacture?
2. How do you source your components to produce the products that you do?
3. How do you collaborate with other stakeholders like the consultancy, contractor, and the owner?
4. What is your contribution in the selection of HVAC systems or components for a building?

Theme 2: Circularity

1. What are your thoughts on CE?
2. What steps are you taking to include circularity in the systems or services you offer?
3. Do you consider the material composition of the products/components considering the scarcity of materials, embodied carbon, and reuse/recyclability?
4. What are the apprehensions about taking used components to prolong the life and reduce waste?
5. What are your apprehensions towards switching to product as a service model?

Theme 3: Circularity in HVAC systems

1. why do you think HVAC systems for buildings are lagging in terms of circularity?
2. What are the risks you might face if you adopt CE?
3. What are your thoughts on taking back components and products for reuse/resell/refurbishment?
4. What are the implications on your financial revenue if you do adopt the product as a service model?
5. What do you think about being involved in the design process of HVAC system for a building?
6. What opportunities do you think exist for HVAC components after the end-of-life stage?
7. Is it also possible to manufacture components that can be deconstructed or disassembled later?
8. Do you think standardization of products is a good step to transition towards CE?

Theme 4: Circularity measures and requirements

1. What needs to change in terms of the design of the building to allow for use of circular HVAC systems?
2. What kind of information or knowledge do you think is needed to include circularity?
3. Do you think government policies or directives are required to push this initiative?
4. Can tax subsidies and exemptions encourage this adoption?

Facility Manager

Theme 1: General Questions

1. How do you collaborate with the rest of the stakeholders?
2. Do you think your expertise can be of value in the design phase?

Theme 2: Circularity

1. What do you know about CE?
2. How helpful do you think are tools like Material Passports and BIM?
3. How do you think these tools can promote circularity?
4. In your experience, do you think that the parts and components that are replaced during maintenance can be reused?

Theme 3: Circularity in HVAC systems

1. What happens to the equipment at the end of their life?

2. How are they disposed?
3. Do you think your early involvement can influence adoption of CE?
4. What are the risks you foresee in the adoption of CE?
5. What are the issues wrt amount of information available about the components that could affect CE adoption?
6. What is your take on product as a service model?
7. What influence will design for disassembly have on repair, maintenance, and the costs associated with it?
8. What is your idea about the use of used components in terms of operating costs?
9. Do you believe having reusability and recyclability in the products will impact life cycle costs?

Theme 4: Circularity measures and requirements

1. What information do you need to prolong the life of an asset?
2. what forms of collaboration can help integrate circularity in HVAC Systems?
3. Do you think policies from the government can aid this inclusion?

Appendix B

Given below are the steps followed to arrive at overarching themes after conducting a thematic analysis and have been explained through an example to arrive at barriers and opportunities.

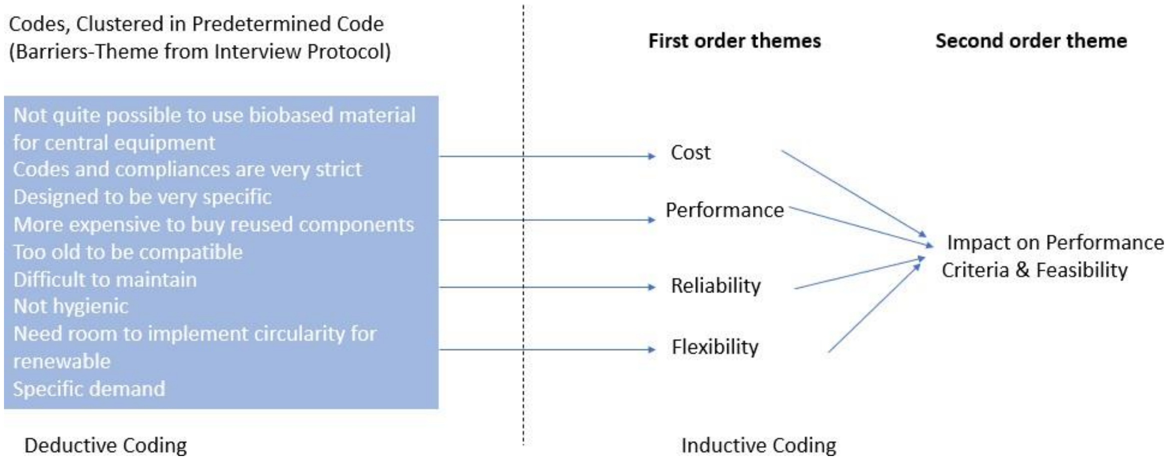

Figure 24: Example of thematic analysis conducted for barriers (Deductive) and Performance & Feasibility (Inductive)

To elaborate, data gathered from 8 interview sessions was clustered under a predetermined code generated from the interview protocol, barriers, and followed a deductive approach. However, the data also expanded into a new theme that emerged and was identified as implications on cost, performance, reliability, and flexibility. These themes were then further clustered into an overarching theme, a second order theme-signifying their performance and level of feasibility. The same was done to identify other patterns as well including *recommendations for the identified strategies*, a theme that emerged from codes that were clustered under the theme, *Circular economy, and current implementation.*

Appendix C

Given below are a few examples highlighting the practical implications of circular interventions on HVAC systems. Knowing the changes or modifications required, consultants and clients can make informed decisions about viability of strategies and can be also used to communicate to other stakeholders like manufacturers and contractors, what is required to incorporate principles of circularity. While the researcher does recognize many other possibilities and changes, the table given below illustrates a few examples or practical scenarios that encapsulate the changes required. This appendix has been structured as changes required for ventilation system and its components in Table 8 followed by changes required for Heating and Cooling systems and its components in Table 9.

Table 8: Practical implication of circularity on Ventilation systems

	CHANGE TO VENTILATION SYSTEM	DUCTS	UNITS	FILTER	TERMINAL UNITS
STRATEGY					
Passive Design	NOT APPLICABLE				
Centralized systems		Flexible ductwork	Makeup air units, valves, VAV boxes		Provision for more grilles and diffusers
Sharing spaces	Same as centralized				
District heating	Same as centralized		Valves and VAV boxes for control		
Prefabricated equipment		Modular/Flexible ductwork	Modular AHUs, humidifiers		
Product as a service model	Comfort as a Service				
Repair		Avoid sheet metal ducts with fiberglass.			
BMS/BAS					
Flexible & Adaptable Design		Modular sheet metal ducts, flexible ductwork	Plug and play, standardized units, use of brackets, hangers, spigots, bolts. Mechanical ventilation with heat recovery for refurbishment.		
Utilising Reusable/Refurbished Equipment		Reuse/Repurpose ductwork after treatment for mold/contaminants	Reuse AHUs, VAV boxes, attenuators	Washable filters, electrostatic filters	Reuse grilles, diffusers after treatment for corrosion
Use of Mono-materialistic components		Sheet metal ducts. Avoid adhesives or rubber for insulation	Avoid adhesive, petroleum- based sheets spraying on Attenuators, VAV boxes, AHUs		Aluminum/Steel coated with C2C approved coatings
Use of renewable sources	No changes required for system				
Use of alternative/biobased materials		Textile, Gatorduct		Filters made of recycled textiles	

Table 9: Practical implication of circularity on Heating/cooling Systems

HEATING & COOLING SYSTEMS		HEAT GENERATION/REFRIGERATION EQUIPMENT	PIPE NETWORK	TERMINAL UNITS
CIRCULAR STRATEGY	Passive Design			
	Centralized systems	• Heat pumps • Combined heat and power plants • Fuel Cells • Use of absorption chillers powered by renewable sources or regenerative energy.	Metal pipes and installations like valves for control and create more thermal zones. Pipe insulation like Calcium silicate, Thermaflex, and other C2C certified insulation.	Radiators coated with solvent free paints. Dry ceiling and wall heating systems with metal pipes.
	Sharing spaces	Same as centralized	Same as centralized	Same as centralized and flexible and adaptable design.
	District heating	District heating/cooling from renewable sources	Same as centralized	Same as centralized
	Prefabricated equipment	Heat pump, Heat exchanger, modular chillers	Prefabricated metal piping	Prefabricated underfloor heating. Modular radiators Infrared Heaters
	Product as a service model	Heat pumps as a service Airconditioning as a service		
	Repair	Modular and standardized heat pumps and boilers	Steel pipes or HDPE pipes	
	Flexible & Adaptable Design	Modular chillers with range of capacity Hybrid VRF (Variable Refrigerant Flow)	Demountable pipe network using bolts, screws, hangers, etc.	Radiators Dry underfloor heating and cooling systems Active Chilled Beam systems VAV boxes fitted with occupancy sensors etc.
	Utilizing Reusable/Refurbished Equipment	Reuse heat exchangers, boilers, heat pumps. Reuse refurbished chillers, cooling towers. Refrigerant can also be reused after proper purification and testing.	Piping network can be reused after inspection, repairing insulation, and testing.	
	Use of Mono-materialistic components		Avoid using permanent glues, adhesives, rubber	Mono-material heating coil like copper tubes or fins.

	Use of renewable sources	• Solar thermal • Heat pumps running on renewables. • CHP supplied by renewables		
	Use of alternative/biobased materials		Tamped hemp as insulating material	

Appendix D

This appendix includes information about the key findings from a discussion with an expert, a consultant in circular building installations, crucial in improving and validating the developed guideline to help consultants design and consider circularity for HVAC systems.

Questions regarding the applicability of the framework for practitioners were posed to the expert. Following this, they explained that this framework could be helpful in several ways. Firstly, it could aid in developing ambitions. Secondly, it could address the common situation where the client is often unaware of their needs. Therefore, providing a holistic guideline that includes both the identification and implication of circularity measures could help streamline the client's understanding. They acknowledged that a similar practice is followed, but the starting point for them is typically the identification of the circular principles. Similarly, this approach categorizes strategies based on their resource loops, suggesting the practical relevance of this framework.

Additionally, when zooming in on the aspects of the framework and identifying the consequences of circularity, they acknowledged that currently, you cannot "have it all." This framework represents this understanding while also highlighting the nuances and necessities of circularity. Highlighting the relevance of the identified strategies, the expert concurred citing that they consider such practices to conform to the principles of circularity. Specifically for the use of reusable components, they agreed that the reuse of AHUs and other central equipment is picking pace and agreed with the limited potential for using biobased materials for central equipment as currently there is no availability in the market.

Lastly, they recommended quantifying the impact for a higher level of accuracy and direct implementation. An example cited by them was to incorporate the use of indicators like Material Circularity Indicator or the Environmental Cost Indicator and identifying expected impact on the lifespans because of each circularity intervention. Moreover, they suggested integrating an organizational perspective as an additional layer in the performance evaluation criteria.