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Dynamic Benchmarking of Building Strategies for a Circular Economy

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Abstract. Increasing building demands from a growing world population puts enormous pressure on natural resources. Management of resource consumption and environmental impacts is therefore vital to secure contemporary and future well-being and progress. Circular Economy (CE) is perceived as an industrial economy model potentially minimizing resource consumption, waste production and environmental impacts by the means of increased material circularity e.g. reuse. In order to promote CE in buildings, there is a need for benchmarks to support building designers in choosing environmentally viable solutions. Although life cycle assessment (LCA) help policy makers and building practitioners to define such benchmarks, benchmark studies often rely on static LCA approaches. Hence, uncertain and unknown dynamic changes during a buildings' long service life influencing the performance of long term sustainable building design principles are not accounted for. Through a literature review the paper at hand identified dynamic technological progress such as resource and energy consumption, energy grid mix, waste management, design and innovation and production efficiency as potentially essential to include when defining realistic CE building strategy benchmarks. How these dynamic factors may affect LCA results were demonstrated through a case study of a concrete column based on a range of possible scenarios. This included estimated future projections and the uncertainty relating to prospective assessments resulting in an output in the form of a span of possible future developments and environmental impacts instead of a single output. Based on the literature review and case study, main challenges of incorporating dynamism within building LCA benchmarking were identified.

1. Introduction

Circular economy (CE) is an industrial economy where the resource flows are managed within a restoring and regenerating capacity by extending resource life thereby avoiding depletion and reducing environmental burdens induced by these resource flows [1]. Thus, CE is of interest to minimize the construction industry's significant contribution to environmental impacts, resource consumption and waste production and both political and industrial initiatives are beginning to form at a greater extent [3–5]. For that reason it is increasingly important to be able to show the designers and decision makers where/how large the environmental benefits of CE are. One way is to establish benchmarks which are essential for comparing performances and establishing future mitigation goals to support building designers choose environmentally viable solutions. Life cycle assessment (LCA) can help establish such benchmarks [2] and is increasingly used by the construction sector and in some recently published CE studies [3,4]. LCA is used in certification schemes such as DGNB that have established benchmarks for LCA using reference buildings i.e. representative buildings for the establishment of benchmarks [2]. LCA benchmark values may also become part of the new Danish voluntary sustainability class in the building regulations [5]. However, the problem is that LCA is a well-developed tool for assessing products with a short service lives and/or have no ongoing inputs and outputs that change in magnitude and origin over time [6] whereas buildings sometimes have a very long service life with ongoing inputs and outputs that change in magnitude and origin over the course of many years or decades. Hence, benchmark studies often rely on static LCA approaches i.e. dynamic factors that can affect the environmental impacts of buildings and building components are not considered clearly limiting the validity of the LCA results [7]. In terms of CE this poses a problem as CE is about prolonging resource life thus designing also for systems operating in the future, not only today. For that reason a forecasting perspective is important for assessing and quantifying the benefits of CE to help guide design decisions today. Although, comparison of LCA results are important in order to develop benchmarks, in terms of CE comparing buildings such as done in e.g. DGNB will not be enough to establish reliable benchmarks. Instead LCA results should be compared against realistic future points of reference to provide a level of confidence when basing the adoption of CE building design strategies on LCA results. Dynamic life cycle assessment (DLCA) is an LCA approach enabling incorporation of dynamic process modelling in the context of temporal and spatial variations in the surrounding society as well as industrial and environmental systems [8]. Hence, the use of DLCA can potentially more realistically predict buildings' environmental performance by acknowledging potentially significant dynamic factors and thus offer a better basis for benchmarks to guide design decisions. However, DLCA research is at its infancy and predominantly applied in other industries and cannot be directly applied to buildings due to their complexity and long service life resulting in dynamic factors having a much longer and more complicated influence on building LCA results [7].

Focusing on the embodied environmental impacts related to the buildings' material resource flow in line with the CE, the paper at hand does not attempt to develop benchmarks for CE building strategies sector but rather explore the difference between using traditional building LCA and forecasting principle from DLCA when developing benchmarks. The paper at hand aims at: 1) through a literature review to create an understanding of the DLCA approach in the context of buildings and DLCA's potential importance to developing relevant benchmarks by identifying which elements of a building LCA can be addressed dynamically as well as which dynamic factors are assumed to be of significant importance to the environmental impacts of buildings' material resource flows and 2) based on the findings of the literature review, conduct a case study of a CE designed concrete column demonstrating how significant dynamic factors may affect LCA results. Furthermore, challenges of incorporating dynamic modelling principles within building LCA benchmarks are discussed.

2. Literature review

The literature review is not intended as an exhaustive study but a summarising representation of the state of art by covering the most recently published and relevant literature on the subject of DLCA focusing on quantifying the environmental burdens from buildings' energy and material flows. The literature review indicates that although DLCA studies within buildings exist dynamism is not incorporated in LCA benchmarks. Additionally, DLCA publications addressing temporal properties in building related LCAs is rapidly increasing, however, DLCAs are performed in various ways resulting in inconsistency and risk of undermining method validity and provide misleading results [6] and DLCA is still in its infancy [7]. Previous studies have found that DLCA results varied greatly when compared equivalent to static results[8]. Furthermore, changes during a buildings service life can in some cases influence the LCA result greatly compared to the production and construction phases [8]. From the literature two perspectives on dynamism are found i.e. dynamism related to the LCA framework and dynamism related to building life cycle stage specific processes such as production, operation and end-of-life. The LCA framework oriented DLCA approaches identified suggest that it is possible to treat any one or multiple of the four ISO 14040 LCA phases dynamically: 1) Goal and scope definition, 2) Inventory analysis, 3) Impact assessment and 4) Interpretation using different modelling methods: a) dynamic process inventories where future potential developments are incorporated into single unit processes, b) dynamic systems where future potential changes in terms of components of systems are accounted for by changing between unit processes, c) dynamic characterisation factors applied in the impact assessment to reflect impact potential change over time, d) dynamic scope and e) and dynamic weighting [6–9]. However, c) and e) have weak links to construction and insufficient research basis [7,8]. A full DLCA i.e. that covers dynamic aspects in all applicable phases and parts of the LCA for all unit processes are in most cases not feasible [6–8]. This is due to excessive data demands compared to conventional LCA, lack of adequate data, increased model complexity, lack of an established methodology, challenges in terms of incorporating dynamic aspect in existing LCA (static) software, or high uncertainty of dynamic process or system properties that is better omitted [6–8]. DLCA that does not exhibit dynamism in all phases or parts of an LCA results in a partially dynamic life cycle assessment (PDLCA) but can however still in many cases provide better/more realistic decision support compared to static LCA [6]. However, appropriate measures must be taken to ensure that use of PDLCA does not bias the results [6]. To avoid potential bias of results by applying PDLCA, system dynamics can be accounted for via the sensitivity analysis i.e. by exploring the effects of dynamisms on the system via sensitivity analysis facilitating illumination of potential issues i.e. temporal dependencies of the result [6]. The other DLCA approach accounts for building life cycle related processes that occurs during production, use, end-of-life and next product system. As previous LCA studies have consistently found that the operational energy consumption dominates most environmental impact categories DLCA in buildings has also mainly focused on buildings' operational energy consumption [10]. E.g. the Danish LCA software LCAbyg calculates both a static and dynamic energy consumption for operation based on a future Danish grid mix scenario for 2050 [11]. However, as some new low-energy buildings have radically reduced energy consumption the operational energy consumption is no longer considered to be the most important contributor to building-related environmental impacts [10,12]. This shifts focus to the buildings' embodied energy and environmental impacts [10,12] which is also in line with the CEs focus on resources. From the literature the dynamic factors related to specific temporal process developments in the building life cycle that are identified to be of significance for the embodied impacts as well as extraordinary relevance to CE are the technological progress related to: resource and energy consumption, compositional changes in energy structures and grid mix where the share of renewable energy is expected to increase in the future, waste management in terms of recovery and renewable rate of resources, design and innovation production efficiency [7,9]. Additionally, dynamic factors such as variation in occupancy behaviour, emissions/resources, environmental systems are also mentioned [5], [8]. Common for all of these dynamic factors are that they are related to (large) uncertainties, mainly related to future technological and political developments yielding many plausible futures. One way to handle future uncertainties is to build scenarios (i.e. scenario exploration) based on possible future trends or even likely trends based on predictive/prospective policies or historic trends (i.e. prospective scenario development based on back-casting) indicating realistic future developments with high probabilities that might have an influence on the environmental performance [6,8]. In addition, several scenarios that encompass a best or worst case scenario could be presented yielding a result span in which future environmental performance are expected to take place [6].

Another issue with building benchmarks is that they can be misguiding as different buildings may show similar results on the overall building level but for different reasons. This is because each building materials' and components' embodied environmental impacts are dependent on different factors such as different service lives, life cycles, dimensions, weight, functions etc. [13]. A systematic decomposition of buildings into their separate functions facilitating the identification of how the relationship of the embodied environmental impacts building elements relate to different building attributes may help predict and may greatly benefit the effort of reducing the embodied environmental impact of buildings even in the early design phase [13]. Ideally benchmarks could be established based on the specific conditions for every building element e.g. the embodied environmental impacts of a foundation is among others dependant on the weight it has to carry [13]. However, an adequate pool/sample of representative buildings are needed to base statistics on and standardize embodied environmental impacts to develop representative and specific benchmarks for e.g. building elements, functions, typologies, geographies, etc. in order relate to other building projects.

3. Case study method

Several studies show that concrete structures generally account for a large share of buildings' embodied impacts [14]. Hence, based on the findings of the literature review the use of dynamic process inventories and dynamic systems within DLCA focusing on energy grid mix, waste management, design changes and production efficiency are explored in a case study of a concrete column, building on an existing static LCA study where two scenarios sT and sD were modelled [15]. sT is a traditional design where the concrete column is casted together with the other concrete making it impossible to separate the column into its constituents for reuse without damage e.g. crushing of the column into concrete gravel for use as road filling and recycling the reinforcement steel to new steel products after a service life of 80 years. sD is where the column is designed for disassembly using large bolted mechanical steel connections from the Finnish company, Peikko, enabling reuse in a new future building after 80 years thereby prolonging the elements' service life and avoiding environmentally burdensome production of new concrete elements based on already existing marketed solutions [16]. Both sT and sD are modelled using a contemporary energy grid mix in all processes. The Danish 2050 energy grid mix scenarios forecast increased shares of waste incineration and renewable energy from wind i.e. the thermal energy will come from: 7% biomass and 93% waste, and electricity will come from: 10% biomass, 7% waste, 3% biogas, 1% natural gas, 76% wind and 3% solar [11,17]. New developments in cement production suggests a future reduction of up to 30% of its current embodied greenhouse gas emission (GHG) [18]. In addition, research on recycling of concrete into new concrete is currently ongoing [19]. Furthermore, future reductions in construction waste are expected as a result of the Danish government's CE strategy [5]. Additionally, with the increase of wind power it is expected that electricity will play an important role in future transport technology [17]. Adding these likely technological progresses to sT and sD resulted in two dynamic scenarios, dT and dD, modelled in accordance with the PDLCA approach. dT is similar to sT however assuming application of the 2050 energy grid in future life cycle processes, 30% less embodied GHG from cement production and higher quality recycling rates in year 80 which further increases in year 160. dD is similar to sD however assuming 2050 energy grid mix for future life cycle processes and 50% lower embodied GHG from transportation in year 80 and similar high quality recycling rates in year 160 as for dT. In year 1 sT and sD are modelled the same as is sD and dD using present grid mix. In year 80 for dT and year 160 for dT and dD, it is assumed that recycling of concrete substitutes a certain amount of virgin concrete that otherwise would have been produced using cement with 30% decreased embodied GHG. For D, the transportation distance is set to the longest possible transportation distance in Denmark of approximately 480 km. Table 1 and 2 provides an overview of how different processes within each life cycle phase are modelled for year 1, 80 and 160 for each scenario. The embodied GHG obtained from the dynamic models, d, are compared to the static models, s, where d reflects a best case scenario and s reflects a worst case scenario where we proceed as we do today. This provides a span in which the future embodied GHG can be expected to take place. All four scenarios were modelled following the LCA methodology stated in the standard EN 15978 using the openLCA v1.4 software and baseline characterization factors from the Centre for Environmental Studies (CML) baseline 2001.

Table 1. Traditional column scenario

		1st life cycle			**2nd life cycle**		
Life cycle phase		**P 1**	**E 80**	**N 80**	**P 80**	**E 160**	**N 160**
sT[4]	Grid mix	Present	Present	Present	Present	Present	Present
	Reinforcement steel	76 kg	99% recycling, 1 % landfill	-	76 kg	99% recycling, 1 % landfill	-
	Concrete 35MPa	1489 kg	90% recycling, 10% landfill	90% virgin gravel substitution	1489 kg	90% recycling, 10% landfill	90% recycling substituting virgin gravel
dT	Grid mix	Present	2050[1]	2050[1]	2050[1]	2050[1]	2050[1]
	Reinforcement steel	76 kg	99% recycling, 1 % landfill	-	76 kg	99% recycling, 1 % landfill	-
	Concrete 35MPa	1489 kg	100% recycling	25% / 75% virgin concrete/ gravel substituting[3]	1489 kg with 30% improved cement production technology[2]	100% recycling	50% / 50% virgin concrete/ gravel substituting[3]

Abbreviations: s =static, d= dynamic, T = traditional, D = design for disassembly, - = no substitution, P = Production, U = Use, T = Transport, E = End-of-life, N = Next product system, Present = Ecoinvent dataset energy grid mix. Sources: [1][11,17], [2][18], [3][5] and [4][15].

Table 2. Design for disassembly column scenario

		1st life cycle	**2nd life cycle**		
Life cycle phase		**P 1**	**T 80**	**E 160**	**N 160**
sD[4]	Grid mix	Present	480 km lorry transport	Present	Present
	Reinforcement steel	76 kg		99% recycling, 1 % landfill	-
	Steel connections	26 kg			
	Concrete 35MPa	1489 kg		90% recycling, 10% landfill	90% recycling substituting virgin gravel
dD	Grid mix	Present	480 km lorry transport with 50% improved transportation technology[3]	2050[1]	2050[1]
	Reinforcement steel	76 kg		99% recycling, 1 % landfill	-
	Steel connections	26 kg			
	Concrete 35MPa	1489 kg		100% recycling	50% / 50% virgin concrete/ gravel substituting[2]

Abbreviations: s =static, d= dynamic, T = traditional, D = design for disassembly, - = no substitution, P = Production, U = Use, T = Transport, E = End-of-life, N = Next product system, Present = Ecoinvent dataset energy grid mix. Sources: [1][11,17], [2][18], [3][17] and [4][15].

As CE focus on resource life extension the functional unit was set to provide the function/service of the column across two component life cycles (i.e. 2 times 80 years). The life cycle inventory (LCI) of the background system was based on the Ecoinvent 3.2 database using system processes to obtain aggregated results, however, switching between unit processes were used to model the dynamic aspects. The foreground system was compiled using the manufacturers' product specifications. The system boundaries include production, waste recovery for reuse, recycling or incineration and disposal by landfilling at end-of-life, and credits for potential reuse, energy recovery and recycling of materials and components in a next product system. Allocation of environmental impacts and credits are modelled following the 100:0 (cut-off) approach of EN 15978. As steel is assumed produced using scrap steel, no environmental crediting is achieved when recycled again [20]. To address uncertainties of the dynamic scenarios dT and dD a sensitivity analysis evaluates the influence of possible sensitive material and energy source input parameters resulting from a 10% input value increase [21].

4. Case study results

Figure 1 shows the life cycle embodied GHG and material flows resulting from the static LCA represented by sT and sD and the PDLCA represented by dT and dD where the size of the arrows approximately represents the amount of the material inputs and output flows. The highest material embodied GHG originates from production of concrete in year 1 for both T and D. However, the embodied GHG of producing column D in year 1 is slightly higher compared to column T due to the use of extra steel for the connections to allow assembly and disassembly. Considering sT, where column T is not suitable for reuse at the first use cycles' end-of-life, supplying a second use cycle with the same kind of column requires production of a new column. Hence, the embodied GHG of column sT originates from production in year 1, and at end-of-life in year 80 treatment of 90% concrete substituting virgin gravel resulting in negative embodied GHG, furthermore 99% reinforcement steel for recycling and 10% concrete and 1% reinforcement steel for landfilling at . During the second use cycle this is repeated. The similar processes are repeated for dT, however, differing as the dynamic aspects stated in Table 1 have been added. Hence, the embodied GHG of column dT comes from production in year 1, and at end-of-life in year 80 treatment of 100% concrete for recycling, where 25% and 75% substitutes virgin concrete and gravel respectively resulting in negative embodied GHG, 99% reinforcement steel for recycling and 1% reinforcement steel for landfilling. In the second use cycle the embodied GHG in year 80 comes from the production of a new concrete column however with 30% less GHG from the production of cement. And at the end-of life in year 160 the embodied GHG comes from treatment of 100% concrete, where 50% substitutes virgin concrete and 50% substitutes gravel resulting in negative embodied GHG, 99% reinforcement steel for recycling and 1% reinforcement ending up in landfills. For sD, the embodied GHG originates from production in year 1, transportation to a subsequent building in year 80 and end-of-life in year 160 from treatment of 90% concrete substituting virgin gravel resulting in negative embodied GHG, 99% reinforcement steel for recycling, 10% concrete and 1% reinforcement steel being. The similar processes are repeated for dD, however, differing as the dynamic aspects stated in Table 2 have been added. Hence, the embodied GHG comes from production in year 1 and transportation to a subsequent building at end-of-life in year 80, however, with 50% less GHG. At the final end-of-life in year 160 the GHG comes from treatment of 100% concrete for recycling, where 50% substitutes virgin concrete and 50% substitutes gravel resulting in negative embodied GHG, 99% reinforcement steel for recycling and 1% reinforcement deposited in landfills. From the accumulated embodied GHG it is seen that the scenario exhibiting the highest embodied GHG is sT with 488 kg CO_2 eq. and the scenario with the lowest embodied GHG is dD with 257 kg CO_2 eq. The accumulated graphs for the static scenarios clearly reveals that that reuse of the column sD to supply two life cycles is less burdensome compared to producing two column sT to supply the same two life cycles. However, when simultaneously looking at the accumulated graphs for the dynamic scenarios, this is no longer the case as the technological progress over time results in dT and dD exhibiting close to a similar performance with 297 kg CO_2 eq. and 257 kg CO_2 eq. respectively.

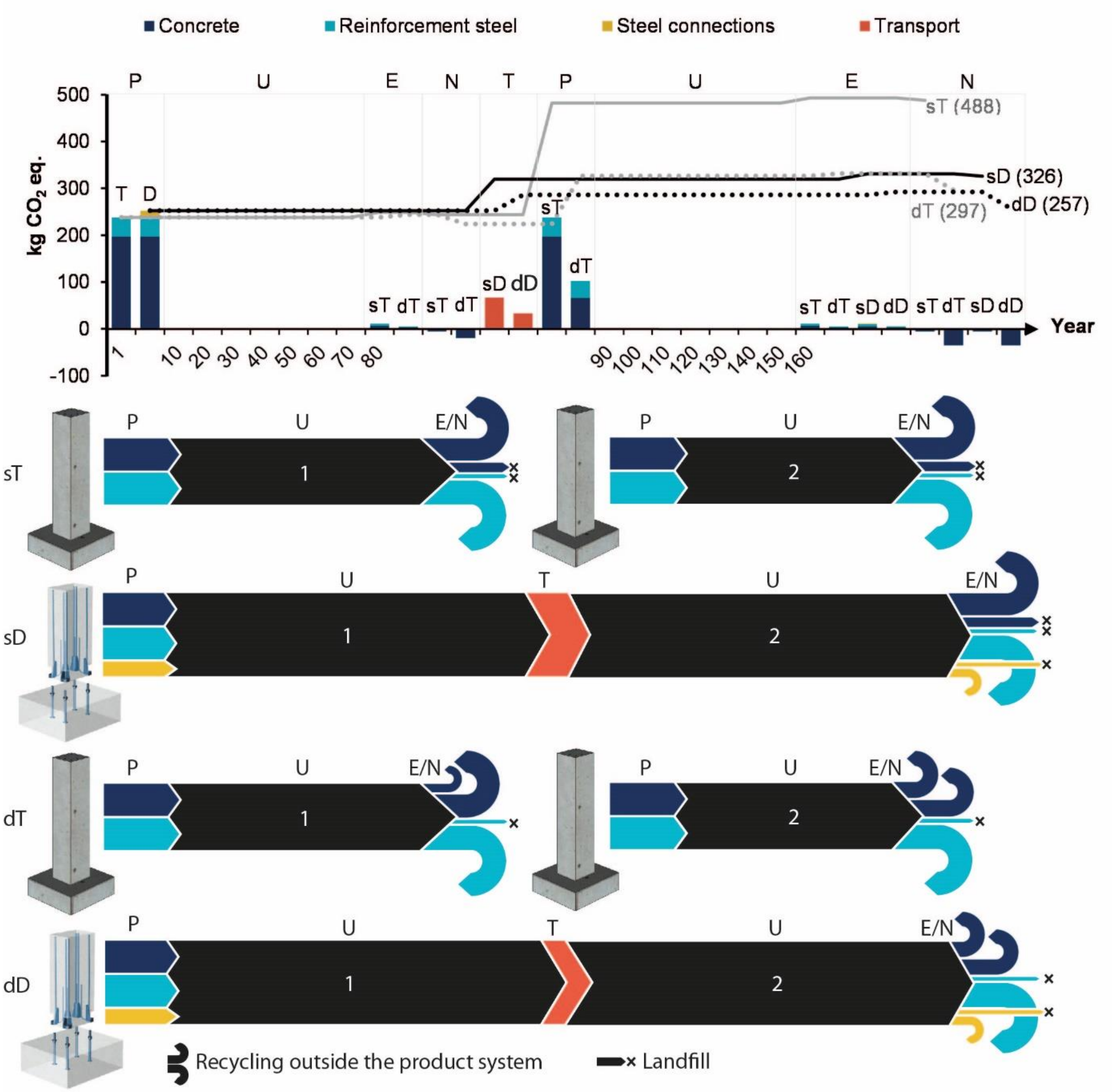

Figure 1. Comparison of life cycle embodied GHG and material flows of the modelled scenarios. Abbreviations: P = Production, U = Use, T = Transport, E = End-of-life, N = Next product system, 1 = first use cycle, 2 = second use cycle, s=static, d=dynamic, T=traditional, D= design for disassembly.

5. Discussion and conclusion

From the example of the concrete column provided here taking into account several life cycles, the static LCA results supports the CE idea that design for disassembly for reuse of building component is environmentally preferable over production of new components. However, when incorporating the technological progress in the dynamic LCA, results show that the environmental performance of a newly manufactured column performs close to the same as reusing an old column, but reuse of the column still performs slightly better. For CE design concepts such as design for disassembly, this could potentially mean that complete neglection of dynamic aspects when developing CE benchmarks can evidently provide false guidance on which design strategies to use on component level and how to best meet future mitigation goals. From the sensitivity analysis it was tested to which extent the output parameters of dT and dD were sensitive towards any of the material and energy source input parameters i.e. if a small change of a 10% increase in the input parameter value would result in a large change in the model results. Table 3 shows that, although the energy source input parameters related to electricity and thermal energy can be qualitatively associated with a high uncertainty, the model output is insensitive to these parameter as the sensitivity coefficients are below 10%, hence, the uncertainty of them will not affect the overall results. However, the output parameters of both dT and dD were found to be very sensitive to a 10% increase in the material input parameters, especially concrete which exhibited a sensitivity coefficient of 75% and 78% for dT and dD respectively. This could be due to the fact that for the column scenario the dynamic technological progresses explored mostly affects the concrete e.g. changes in waste management and production efficiency. For that reason the uncertainty of other technological progresses may influence the results even more compared to the future energy grid mix.

Table 3. Parameter sensitivity coefficient of dynamic scenarios dT and dD

<table>
<tr><th rowspan="3">Material parameters</th><th>Scenario</th><th colspan="2">Concrete</th><th colspan="2">Reinforcement steel</th><th colspan="2">Steel connections</th></tr>
<tr><td>dT</td><td colspan="2">74%</td><td colspan="2">30%</td><td colspan="2">-</td></tr>
<tr><td>dD</td><td colspan="2">78%</td><td colspan="2">19%</td><td colspan="2">7%</td></tr>
<tr><th rowspan="3">Electricity parameters</th><th>Scenario</th><th>Biogas</th><th>Biomass</th><th>Natural gas</th><th>Solar</th><th>Waste</th><th>Wind</th></tr>
<tr><td>dT</td><td>0.004%</td><td>0.019%</td><td>0.019%</td><td>0.011%</td><td>0.115%</td><td>0.045%</td></tr>
<tr><td>dD</td><td>0.000%</td><td>-0.021%</td><td>0.021%</td><td>0.013%</td><td>0.146%</td><td>0.056%</td></tr>
<tr><th rowspan="3">Thermal energy parameters</th><th>Scenario</th><th colspan="3">Biomass</th><th colspan="3">Waste</th></tr>
<tr><td>dT</td><td colspan="3">0.04%</td><td colspan="3">9.96%</td></tr>
<tr><td>dD</td><td colspan="3">0.01%</td><td colspan="3">2.13%</td></tr>
</table>

However, the study at hand is limited in its scope as it only explores the influence of incorporating dynamism in an LCA of a concrete column focusing only on embodied GHG and may obviously overlook other potentially important aspects of incorporating dynamic aspects in CE benchmarks. E.g. in terms of CE, dynamic LCA does not show how the column performs in terms of resource scarcity. Furthermore, this study includes technological progress relevant in a Danish perspective for the particular column in question; however, influencing dynamic factors may differ greatly depending on the geography. Other developments relevant for the concrete column may also have been overlooked. The technological development and influence of dynamism on the environmental impacts of another CE designed building component may also differ greatly from that of the column making it difficult to define general benchmarks both on building and component level. Thus, CE benchmarks could, as a starting point, focus on where the largest environmental and resource burden improvement potentials lies and in this way facilitate the progression to a more sustainable development of buildings. In addition, the study only considers embodied GHGs, however, the performance of the column may differ when considering another environmental impact category. However, it is difficult to develop benchmarks on the basis of the majority of impact categories due to burden shifting between the impact categories. Although, some LCA software tools include dynamic factors for buildings such as the Danish LCAbyg software which includes forecasted Danish energy grid mixes for 2050 for the operational energy consumption of the building, implementing the dynamic factors' influencing the embodied environmental impacts of each building component is a (much) larger challenge as it requires many alterations to a vast number of (inventory) datasets. However, as a starting point datasets could be designed in a more modular way to also implement dynamic energy grid mix(es) influencing the embodied energy and environmental impacts and thus allow for easier exchange of energy processes. The study at hand also shows that CE requires a different way of conducting LCA in order to quantify future benefits of CE for long-lived building components i.e. accounting for several component life cycles instead of just the first. Despite the limitations of the study, basing benchmarks *on* a more dynamic LCA approach i.e. a range of possible scenarios including estimated future projections and the uncertainty relating to prospective assessments results in an output in the form of a range of possible future developments and hence a range of environmental impacts as demonstrated herein. Such a probabilistic set of results is likely to provide a more meaningful, realistic and accurate decision basis supporting a sustainable development in the building sector.

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