LCC and LCA of dynamic construction in the context of social housing

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Short Summary

Continuously changing household needs and evolving building standards require a frequent upgrade and renovation of our existing residential building stock. A lack of adaptability of buildings, however, often leads to destructive interventions, resulting in financial and environmental impacts. The goal of this paper is to contribute to the search for new design concepts enabling easier and more cost-effective upgrade and renovation of buildings. It should moreover contribute in achieving a lower life cycle environmental impact. A more dynamic design is evaluated in the specific context of a social housing project in Mechelen (Belgium). In this context, building elements with reversible detailing techniques facilitating disassembly and component reuse are compared to more traditional static elements. The benefits and drawbacks are assessed at the building level using a life cycle approach of economic and environmental aspects, i.e. a Life Cycle Costing (LCC) and Life Cycle Assessment (LCA). Different renovation scenarios are simulated focussing on the internal restructuring of the housing units. Two alternatives were investigated: dynamic assemblies of all internal walls versus dynamic assemblies of only those internal walls which are expected to change more frequently. The analysis revealed that the building concept and layout are important for making more dynamic design beneficial or not. Building layouts which provide opportunities for change generally require limited constructive adaptations during the building life span. Application of dynamic assemblies to only those walls which are assumed to be changed in future is then preferred over an application to all internal walls. This could be called a ‘selective’ approach. Such a ‘selective’ approach can result in life cycle environmental benefits while the additional financial costs remain limited.

Keywords:adaptability; building level, life cycle assessment; life cycle costing; renovation.

1. Introduction and objectives

Continuously changing household needs (e.g. due to demographic changes and fluctuations in household composition), evolving building standards (e.g. comfort standards and energy performance regulations) and changing performance desires (e.g. improved acoustical performance or fire resistance) require a frequent upgrade and renovation of our existing residential building stock. A lack of adaptability of buildings, however, often leads to destructive interventions (i.e. demolition works), resulting in financial and environmental impacts. To avoid these, a more dynamic design approach can be proposed, using concepts like disassembly, adaptability, transformability and multi-functionality. The basic principle is the integration of time as design parameter in order to enable buildings to deal with changing needs over their building life cycle [1].

The goal of this paper is to apply and evaluate a dynamic design approach in the specific context of the upgrade of the social housing neighbourhood “Mahatma Gandhi” in Mechelen (Belgium). The paper is based on a research project commissioned by the Public Flemish Waste Agency (OVAM), looking at adaptable design in buildings [2]. The focus is set on the evaluation of a number of representative renovation scenarios at the building level, considering dynamic alternatives for internal wall systems (i.e. assemblies using reversible detailing techniques, in order to facilitate disassembly and component reuse) [1]. Based on a life cycle approach, the financial and environmental benefits and drawbacks of these dynamic alternatives are compared with traditional solutions.

In the subsequent section the assessment method is briefly summarised, including Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) and the dynamic design scenarios. Section three focusses on the case study, describing the results of both a qualitative and quantitative assessment. Some conclusions are drawn in the final section.

2. Methodology

2.1 General

The financial and environmental assessment method used for the evaluation of the dynamic building solutions is based on the methodology developed in the SuFiQuaD (“Sustainability, Financial and Quality Evaluation of Dwelling Types”) research project which proposes an integrated method combining economic and environmental impact calculations during the whole building life cycle, i.e. Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) (Fig. 1) [3],[4]. This means that not only the initial construction stage is taken into account but also the use and maintenance, and the end-of-life (EOL) stage of buildings and subparts. With such approach the long term advantages and/or drawbacks of dynamic design solutions of buildings can be analysed over the total building life cycle.

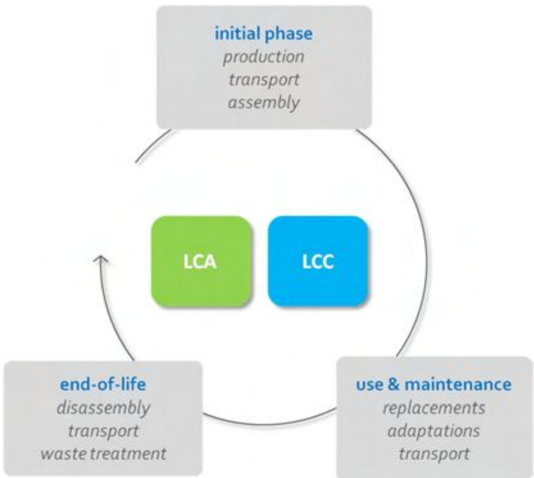


Fig. 1: Integrated life cycle approach in buildings [1]

Another important feature of the SuFiQuaD methodology is the evaluation structure based on the element method for cost control [5]. The basic principle is the hierarchical subdivision of the building in functional elements (e.g. walls, floors, technical installations) for which financial and/or environmental data can easily be calculated. A distinction can be made between five scale levels: building materials (e.g. brick, mortar, plaster), work sections (e.g. brickwork, plasterwork), building elements (e.g. internal wall including finishes), buildings and neighbourhoods (Fig. 2). This hierarchical structure allows using easily the results from the lower scale level for analysis at the higher scale levels. In the context of the research presented, the dynamic design approach was analysed at three scale levels: the building element level, the building level and the neighbourhood level. This paper focuses on the results at the building level.

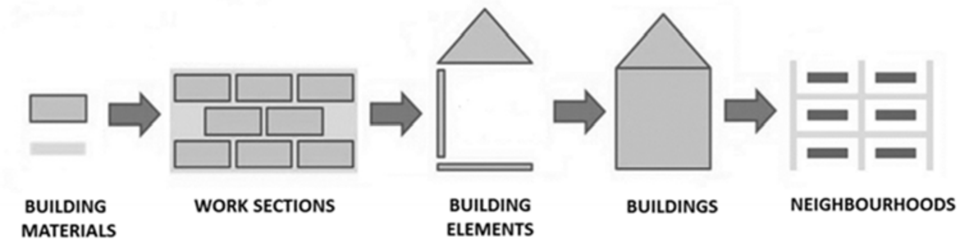


Fig. 2: Element method for cost control and scale levels [2]

In the subsequent paragraphs the applied LCC and LCA method and the scenarios used for the life cycle analysis are explained in more detail.

2.2 Life Cycle Costing (LCC)

The financial costs which occur during the different life cycle stages are assessed via an LCC. These include the costs for material acquisition, the labour and indirect cost, costs for transport and EOL treatment. The financial data are based on Belgian cost databases and product specific data from catalogues and tenders (for the cost estimation of dynamic assemblies) [1]. Future costs are integrated with initial costs by calculating their present value. The following is assumed – based on Belgian statistical data - regarding the economic parameters [1]:

- Inflation rate: 2%
- Real discount rate (above the inflation): 2%
- Real growth rate labour costs (above the inflation): 1%
- Real growth rate material costs (above the inflation): 0%

2.3 Life Cycle Assessment (LCA)

The environmental impact assessment is based on the LCA method developed in the MMG ("Milieugerelateerde Materiaalprestatie van Gebouwelementen") research project, commissioned by the Public Waste Agency of Flanders (OVAM) [6]. This project focuses on the elaboration of an evaluation method for the environmental performance of building elements, adapted to the Belgian context. Besides individual impact indicators, the MMG assessment method allows to assess the environmental impact based on an aggregated indicator, expressed in environmental costs (external costs caused by environmental impacts). In this paper, this monetary indicator is used to evaluate the environmental impact of the proposed dynamic assemblies for internal walls. The environmental impact simulations are made with the Simapro software using the Ecoinvent database (version 2.2) [7][5],[8], which was adapted to the Belgian context (replacing the Swiss electricity mix and transport processes by European corresponding processes).

2.4 Service life scenarios

Scenarios must be defined regarding the life span of buildings and the replacement of building elements and subcomponents in order to evaluate the benefits and/or drawbacks of using dynamic construction. Based on the methodology used in the PhD research of Paduart [1], service life scenarios are defined at three levels: building, building element and subcomponent (Fig. 3). For the *building*, an average life span of 60 year is determined as representative for residential buildings in Belgium [3]. At the *building element* level, a functional service life is used to take into account the changing needs of residents and building standards. Based on a survey among social housing companies [1], the following scenarios are defined:

- Scenario without periodic intervention
  The building element undergoes no major renovation interventions during the building life span (i.e. functional service life equals 60 years), except for the replacement and maintenance of subcomponents at the end of their technical service life.

- Scenario with periodic intervention
  The building element position is altered due to major renovation during the building life span. For internal walls a periodic turnover of 15 year is defined. When the functional service life is exceeded, building elements are replaced by identical new components, except for dynamic assemblies (Design for Disassembly – DfD) where disassembly and reuse of subcomponents can take place (Fig. 3).

Finally, a technical service life is attributed to the analysed *subcomponents* based on reference values from literature for the building sector [9]. For this study average values are used for the simulations. When the technical service life of subcomponents is exceeded, the subcomponent is replaced, eventually together with adjacent subcomponents if those are connected with irreversible connections [1].

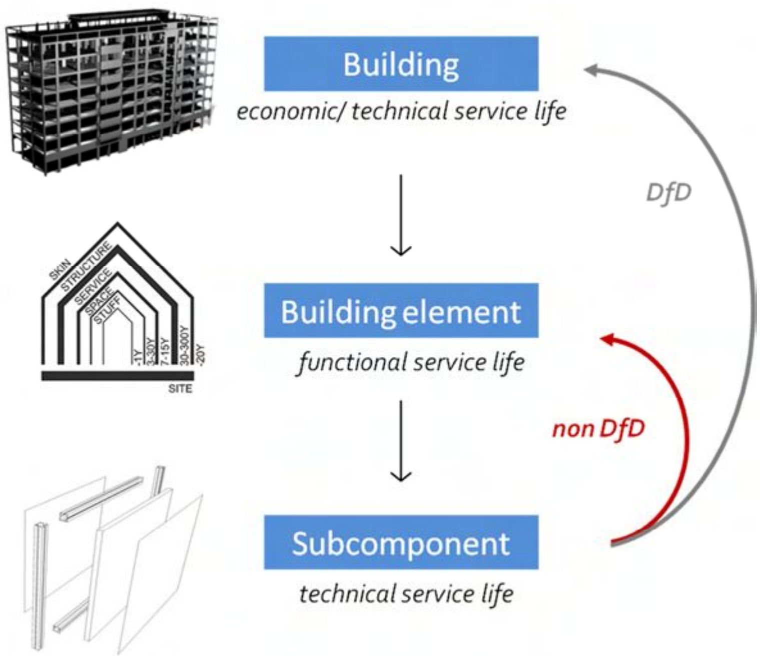


Fig. 3: Service lives on three levels: building – building element – subcomponent [1]

3. Evaluation of case study at the building level

The dynamic design approach is applied and evaluated in the specific context of the upgrade of the social housing neighbourhood “Mahatma Gandhi” in Mechelen (Belgium). Besides the renovation of existing buildings the project includes the demolition of a number of outdated apartment buildings that will be replaced by new collective building blocks (subdivided in 3 parcels).

The case study consists of the first building block (parcel 1) designed by KPW-architecten (Fig. 4). This building is composed of a mix of one-bedroom and two-bedroom apartments. A representative housing unit with two bedrooms is selected for the analysis at the building level (Fig. 4). Before starting the quantitative life cycle analysis of this building block - as described in the previous section - the original building renovation design was analysed (qualitatively) to investigate to what extent dynamic concepts were already integrated. This qualitative analysis was done for three aspects: the construction method, the characteristics of the building layers (*structure*, *circulation*, and *service)* [11], and the plan layout of the housing units. Based on this analysis renovation scenarios, including dynamic assemblies for internal walls, were proposed for the quantitative assessment.

Fig. 4: Ground floor plan (left) and perspective view (right) of the building block (Parcel 1 – neighbourhood Mahatma Gandhi) [10]. The red circle indicates the analysed housing unit.

3.1. Qualitative assessment of the building

3.1.1 Construction method

The buildings of parcel 1 are constituted of masonry walls and concrete floors. This traditional construction method is characterized by irreversible connections (i.e. use of cement mortar) making disassembly and reuse of subcomponents impossible (Fig. 5). In the quantitative assessment (§ 3.2) dynamic alternatives for internal walls are simulated at the building level and compared with the traditional masonry walls.

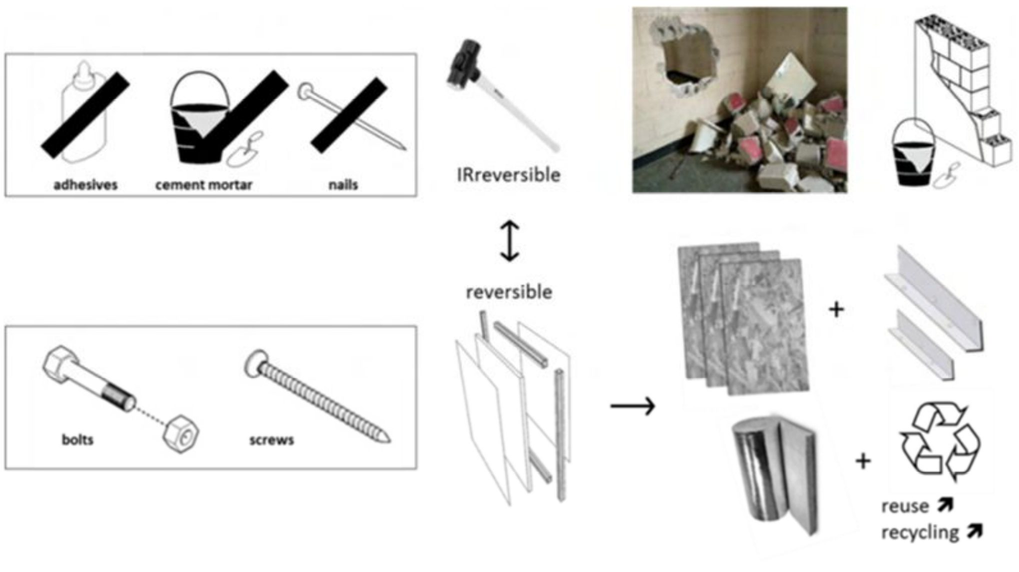


Fig. 5: Static versus dynamic assemblies [1]

3.1.2 Building layers: Structure, Circulation, Services

An analysis of the building layer characteristics identified the opportunities and limitations for adaptability (Fig. 6). The facades, partitioning walls and some internal walls consist of a structure of loadbearing walls. Loadbearing walls can be an obstacle for future adaptations of the layout of housing units. Concerning the circulation, vertical circulation (staircases and elevators) is grouped and the apartments can be accessed via an external gallery. This organisation does not impede the internal subdivision in housing units. Finally, technical services are clustered in central technical ducts increasing the plan flexibility.

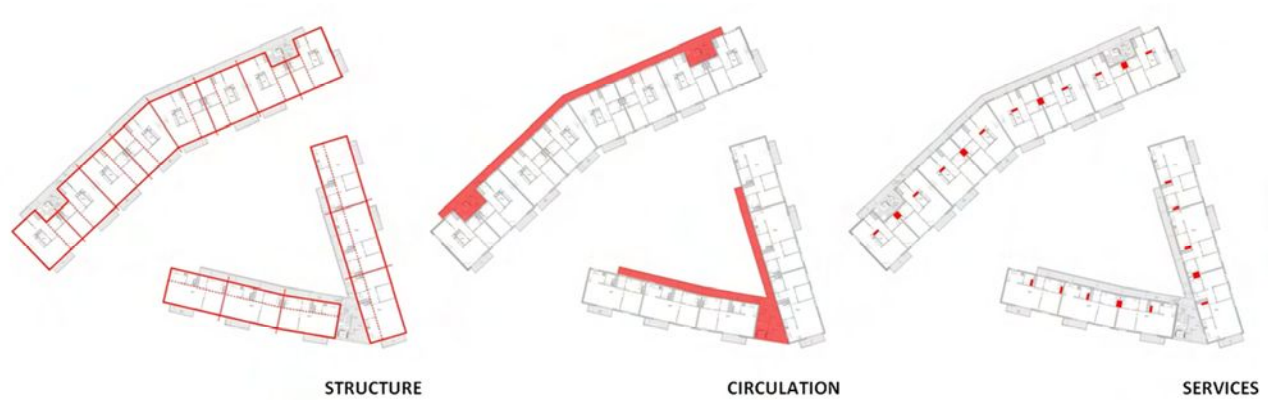


Fig. 6: Analysis of the building layer characteristics: structure, circulation and services (Parcel 1 - neighbourhood Mahatma Gandhi) [2]

3.1.3 Plan layout housing unit

The housing units are characterized by their flexible plan layout. Attention is paid to the grouping of rooms (distinction between living areas and technical and wet rooms) and the clustering of technical ducts, in order to increase the possibilities for future adaptations of the dwelling. Moreover the configuration of the plan lay-out is adapted to wheel chair users (dimensioning of space considering the wheelchair turning radius)

Fig. 7: Flexibility of the analysed housing unit [2]

3.2 Quantitative assessment of renovation scenarios for a housing unit

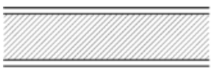
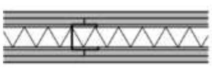
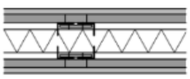
The quantitative analysis at the building level is carried out in three steps. In a first step, renovation scenarios for the internal restructuring of the dwelling are defined. In this paper two scenarios for the transformation of the housing unit from a two-bedroom to a one-bedroom apartment are discussed (Fig. 8 and Fig. 12). As is shown in the figures, the dwelling consists of fixed-positioned internal walls (i.e. walls undergoing no intervention during the building life cycle, except the periodic replacement of subcomponents) and variable-positioned internal walls (i.e. walls of which the position is altered in the course of the building life cycle).
In a second step, the two renovation scenarios at the building level are translated into scenarios for the internal walls. This is done by defining the use period (i.e. period within which the wall is used in the housing unit) and the periodic turnover of each internal wall. Based on these wall scenarios the life cycle environmental impact and financial cost can be calculated for each internal wall type (per m^2 of wall).

In a final step, the LCA and LCC results at the element level (i.e. of the internal walls) are translated to the building level by multiplying the results per m^2 wall by their respective ratio (i.e. m^2 wall/ m^2 floor area). The final results at the building level are then expressed in cost and impact per m^2 floor area.

For the simulations three categories of internal walls have been analysed (Table 1) going from traditional (static) wall systems (masonry walls and dry walls) to dynamic assemblies (Design for Disassembly (DfD) walls, using reversible connections and reusable subcomponents) [2].

Besides the evaluation of the different variants described in Table 1, two alternatives are compared per renovation scenario: the use of dynamic assemblies for all internal walls (simulations "1 wall type") and a selective approach focussing on dynamic assemblies for the variable-positioned walls (simulations "2 wall types").

Table 1: Composition of the analysed internal wall categories [2]

Category	Composition	Thickness
 Masonry wall	- brickwork:	
	a) perforated clay bricks (case study)	140 mm
	b) cellular concrete blocks	150 mm
	c) hollow concrete blocks	140 mm
	- plaster + painting	12 mm
 Dry wall	- metal studs	50 mm
	- mineral wool	40 mm
	- gypsum plasterboard	12.5 + 12.5 mm
	- painting	
 DfD wall	- metal framework	50 mm
	- glass wool	40 mm
	- OSB boarding+	15 mm
	a) MDF boarding	12.5 mm
	b) gypsum fibreboard	12.5 mm
	c) gypsum plasterboard	12.5 mm
	- painting	

3.2.1 Renovation scenario 1: Transformation from a two-bedroom to a one-bedroom apartment with an enlarged living room

In the first renovation scenario a two-bedroom apartment is transformed into a one-bedroom apartment by using the small bedroom as extension of the living room (Fig. 8). Moreover the wall between the kitchen and the living room is removed to create an open kitchen. This renovation scenario can be translated into wall scenarios (Fig. 9), looking at four consecutive periods of 15 years (year 0 until year 15, year 15 until year 30, year 30 until year 45 and year 45 until year 60) in which the apartment is switched from a two-bedroom to a one-bedroom apartment and vice-versa. A distinction can be made between fixed-positioned walls (red walls in Fig. 9) and variable-positioned walls (orange and yellow walls in Fig. 9). For the walls with an interruption of the analysis period (the yellow walls are not present in the housing unit in period "15-30 year" and "45-60 year") the assumption is made that dynamic assemblies are stored (or eventually used in another dwelling) in order to be reused later in the housing unit.

Fig. 8: Renovation scenario 1 (transformation from two-bedroom apartment to one-bedroom apartment) [2]

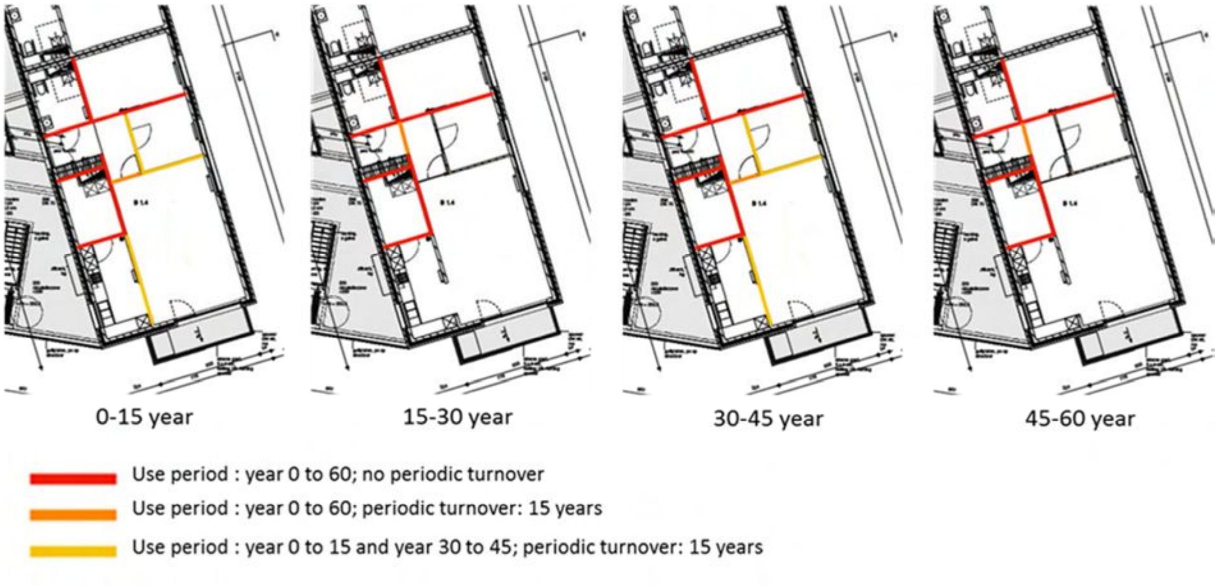


Fig. 9: Wall scenarios in renovation scenario 1 [2]

The LCA results (Fig. 10) show that dynamic assemblies for all internal walls (simulations "1 wall type") are not beneficial compared to masonry walls. This is due to the design of the floor plan-layout which requires a low number of interventions in order to transform the housing unit from one typology to another. When a selective application of dynamic assemblies is chosen (simulations "2 wall types"), the life cycle environmental costs can be reduced. The reduction compared to the "1 wall type"-simulations is however limited because a large part of the internal walls (yellow walls in Fig. 9) are moved to another housing unit during the building life cycle, so that the benefits of component reuse are allocated to that unit.

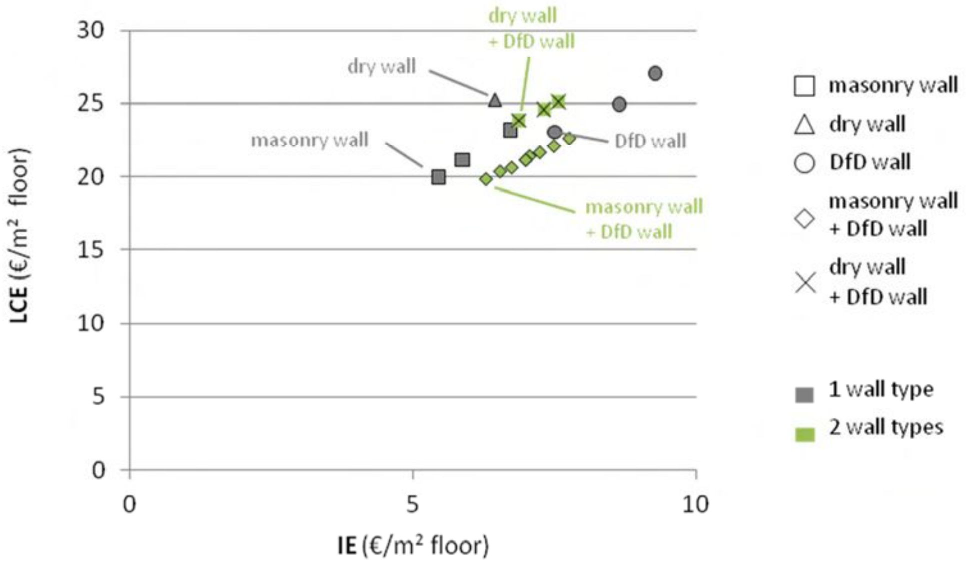


Fig. 10: Overview of the initial environmental costs (IE) and life cycle environmental costs (LCE) for renovation scenario 1 for simulations with 1 or 2 wall types [2]

Concerning the financial evaluation (Fig. 11), the “1 wall type”-simulations show that dynamic assemblies can compete with masonry walls (cost reduction resulting from the pre-assembly of dynamic variants [1]) but are more expensive than dry wall systems (the labour costs for disassembly and reassembly of dynamic variants are higher than the saved material cost resulting from component reuse [1]).

A selective approach for the use of dynamic assemblies (limited to variable-positioned walls) in combination with masonry walls can be interesting (decrease of the initial and life cycle financial costs compared to the use of masonry walls for all internal walls). On the other hand a combination with dry wall systems results in a limited additional cost compared to the generalized use of dry walls.

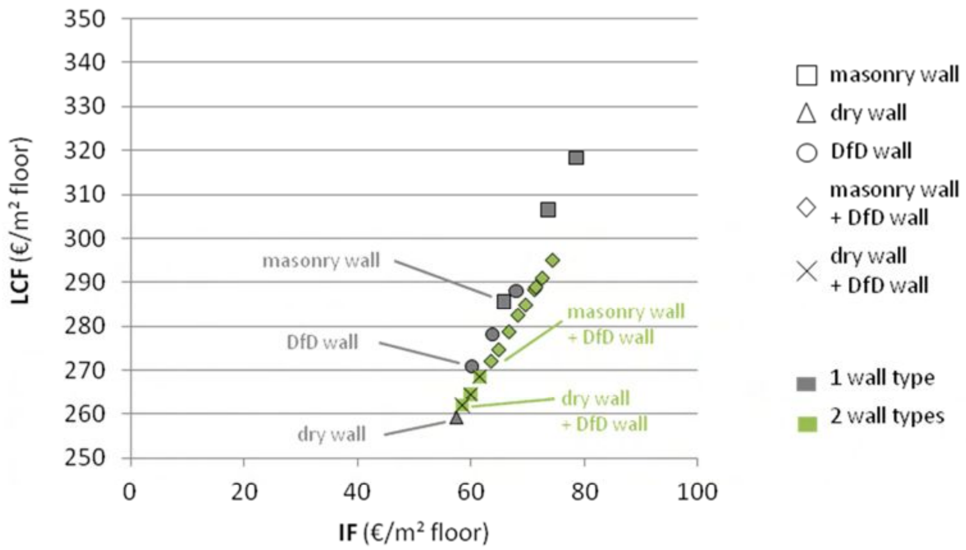


Fig. 11: Overview of the initial financial costs (IF) and life cycle financial costs (LCF) for renovation scenario 1 for simulations with 1 or 2 wall types [2]

3.2.2 Renovation scenario 2: Transformation from a two-bedroom to a one-bedroom apartment with a living room subdivided in a sitting and eating room

The second renovation scenario (Fig. 12) is similar to the previous scenario, except that a part of the internal walls can be reused to divide the living room in a sitting and eating room. This renovation scenario enables to evaluate the impact of higher reuse capacity of internal walls inside the housing unit and the possible environmental and economic benefits of dynamic assemblies. The wall scenarios are shown in Fig. 13.

The LCA and LCC results show the same trends as in renovation scenario 1. From an environmental point of view, a generalized use of dynamic assemblies is not beneficial while from an economic point of view, dynamic assemblies for all internal walls can compete economically with masonry walls but are still more expensive than dry wall systems. A selective approach of dynamic variants results in a higher reduction of environmental costs, compared to renovation scenario 1. This is the direct consequence of the higher reuse of internal walls inside the housing unit. From a financial perspective, a selective approach of dynamic assemblies is advantageous in combination with masonry but leads to additional costs in combination with dry wall systems. Compared to renovation scenario 1, the additional costs are even higher because of additional disassembly steps due to the higher reuse of internal walls inside the housing unit.

Fig. 12: Renovation scenario 2 (transformation from two-bedroom apartment to one-bedroom apartment) [2]

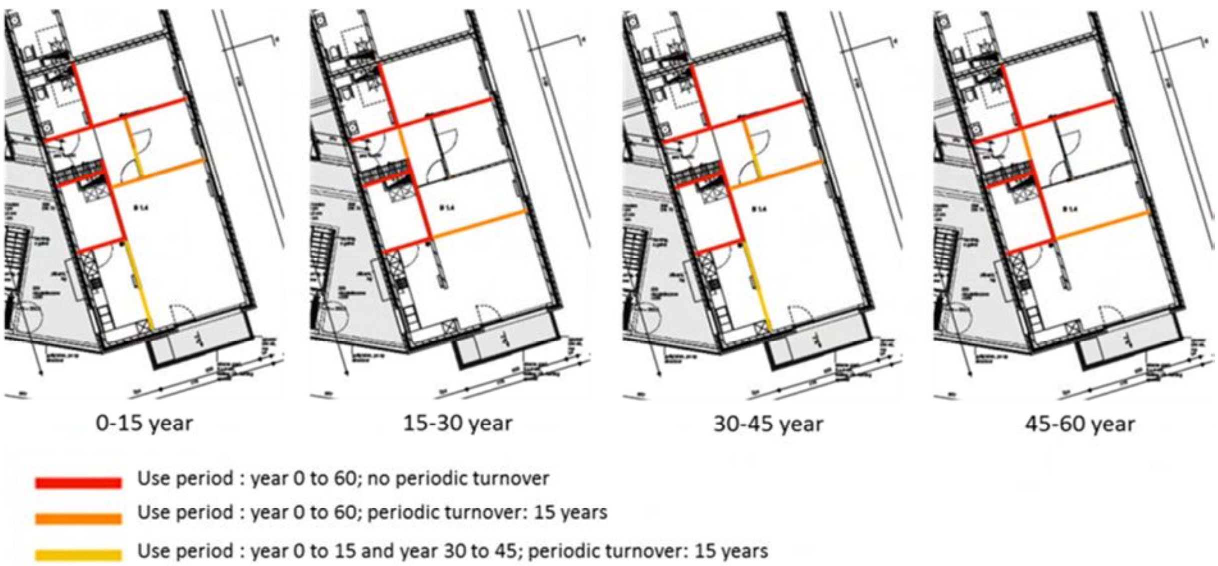


Fig. 13: Wall scenarios in renovation scenario 2 [2]

4. Conclusions

It can be concluded that the building concept and layout are important to make dynamic design beneficial or not. The qualitative assessment of the housing unit revealed that different aspects related to adaptability were integrated in the design proposal of the case study (flexible plan-layout, space and room clustering, adaptability for wheel chair users, external circulation). In consequence, renovation scenarios only required limited interventions and made a generalized use of dynamic assemblies not beneficial, neither from an environmental nor financial perspective. Instead, a more selective application of dynamic assemblies, i.e. to only those walls which are assumed to be changed in future, was proven to be preferred. This selective approach can result in life cycle environmental benefits while the additional financial costs remain limited.

As the conclusions drawn are only valid for the analysed case study with a flexible and polyvalent plan layout, it might be that the advantages of dynamic assemblies were not fully highlighted. It is therefore recommended to apply the same analysis to other case studies. This would allow a more representative picture of the benefits and drawbacks of dynamic assemblies at the building level. Furthermore research should be done about the impact of scenarios for the renovation frequency and service life span of subcomponents. Based on sensitivity analysis at the element level [1], it is expected that those parameters can have an important influence on the evaluation results.

5. Acknowledgements

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