INDICATORS FOR FUNCTIONAL SERVICE LIFE OF BUILDING STRUCTURES

R. Blok[1], P. Teuffel[1]

[1]Department of the Built Environment
TU/e University of Technology
Eindhoven, 5600 MB, The Netherlands
e-mail: R.Blok@tue.nl; P.M.Teuffel@tue.nl

Keywords: Functional Service Life, Buildings Structures, Flexibility, Estimated Service Life, Sustainability.

Abstract. *The Estimated Service Life, ESL, is of a major influence in many building assessments. The comparison and optimization of design alternatives depend on the accuracy of this ESL. More and more the Functional Service Life rather than the Technical Service Life is decisive in how long a building can be used. It is expected that the Functional Service Life is influenced by the ability of the building to accommodate changes to (parts of) the building during its Service Life. Flexibility is here seen as a property of the building that represents the building's ability to change and adapt. A method to quantify and score Structural Flexibility is applied to two groups of buildings, in order to find a possible relation between Structural Flexibility and the Service Life of a building. The first results of this test indicate that it is possible to assess buildings on Structural Flexibility and indicate that there is a relation of this property with the survival probability of buildings. However, the used methodology to assess structural Flexibility needs further development..*

1 FUNCTIONAL SERVICE LIFE

1.1 Life Cycle Assessment and Service Life

The estimated service life of a building, the ESL, is used in Life Cycle Assessments of buildings to assess for example environmental impacts. In [Blok, 2006] it has been shown that the Service Life of a building is of major influence in the buildings final sustainability performance. Figure 1 clarifies this with a theoretical example. The graph shows the impact relation Energy- Materials- Service Life. Depending on the length of the Service Life environmental impacts (in the example global warming potential in CO2 eq) of the materials used for the building (covering the life cycle of the buildings and demolition or deconstruction) is calculated in impact per year of use. Added to this is the yearly energy use (or in the case of the example: the yearly energy production) of the building. The total annual impact thus depends on how long the building is in service.

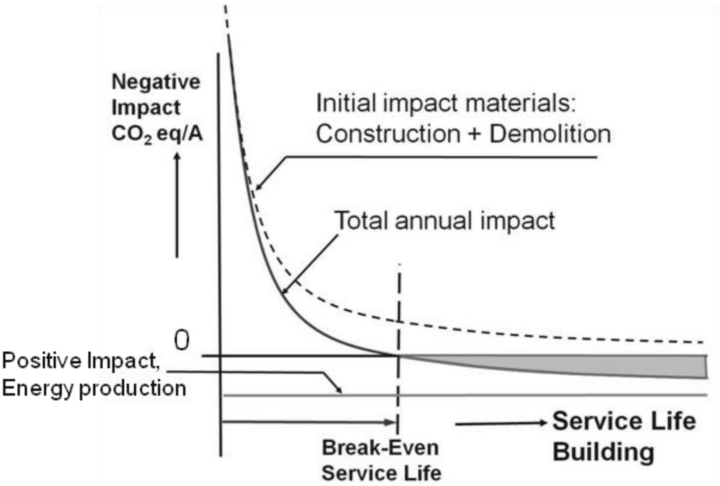


Figure 1; Relation of C02eq impact per year of use versus the realized Service Life of a building, showing when CO2eq-neutrality is achieved.

In this simplified approach it can be seen that it is depending on the on the final length of this achieved Service Life, whether the buildings is actually an energy consuming, energy neutral or energy plus building.

Following the Life cycle and stages a to c of EN 15978 [..] the total annual impact can be described (1) as:

$$I_{annual} = (I_{(a+c)\ init.} / ESL) + I_{(b)} \tag{1}$$

In which

I_{annual} = Total Building Impact per year of use caused by the materials and energy (life stages a to c)

$I_{(a+c)\ init.}$ = Building Impact associated with the initial materials (life stages a and c: construction, deconstruction / demolition)

ESL = Estimated Service Life

$I_{(b)}$ = Impact caused by annual energy use/ production and annual materials used during the use stage b.

It is clear that the accuracy of the total yearly impact *I annual* is also directly depending on the (in)accuracy of the Estimated Service life (ESL). From comparison of already demolished building with reused buildings we learn that differences in Service Lives of buildings can easily range from 30 to 80 years. A factor of two (2) or more between the ESL and the actually achieved buildings Service Life: the Functional Service Life (FSL) is therefore not uncommon. Sometimes simply a Reference Service Life (RSL) of 50 years is assumed, This RSL can be adjusted using factors [ISO TC59 2008].

The Functional Service Life of a building is here defined as: The period of use (from completion until end of use) during which a building continues to fulfill the (possibly changing) demands and functional requirements of its users, if necessary with changes and adaptations to parts of the building.

When the FSL differs very much from the ESL the assessment of the building impacts, indeed the whole of the LCA, despite the accuracy in the impact calculations, can become very inaccurate. It becomes almost impossible to optimize or compare different building solutions. To improve Sustainable Building Assessments the Estimated Service Life of a building should receive much more attention and needs to be improved. [Nuenen, 1994] proposed in improved factor Method for the ESL and the use of influence factors with a probability distribution.

1.2 Service Life of a Building

The Service Life of a building depends on a wide range of different influencing factors. Depending on the different viewpoints of the different stakeholders, different Service Lives can be defined. Table 1 shows these Service Lives with their most important aspects, grouped according to their basic nature of influence. Which of the Service lives is finally decisive in the decision process regarding the end of life of a building depends on how different stakeholders may each give different values and weights to these factors and how strongly they can influence this decision process. Economic factors may often be decisive.

From an engineering point of view engineers used to focus on the Technical Service Life. Maintaining a sufficient structural safety throughout the buildings Service Life here has the main attention. But technical aspects are also influential on the Functional Service Life. There are some reasons why the Functional Service life of a building is now becoming more important and often decisive in the decision between reuse versus demolition.

Cultural Service Life	Historical value Cultural value Architectural Style, Branding: contribution to Image perception of organisations and users,
Economical Service life	Returns on investments versus interest, costs for owners and use, f.i. maintenance-costs. Cost for demolition/ deconstruction End of life value Market developments in real estate property Market Developments of building related costs Development of local land-prices
Technical Service life	Structural Safety, Reliability level of structure versus consequence classification Degradation mechanisms: material deterioration, corrosion, fatigue, thaw- freeze cycles, etc. Hazardous loadings
Functional Service Life	Usability Flexibility, options to accommodate changing requirements Adaptability for changing requirements: spatial re-configuration, changing/ upgrading of building layers, for example façade, services, possibilities for building extensions Re-use

Table 1; Different Service Lives can be decisive, depending on viewpoints of stakeholders

One reason for this is that user requirements of occupants and organisations can change quite fast. The way that organisations (re-)structure their way of working in connection to the use of the building-accommodation seem to be changing more or less in step with the increase in the dynamics of our society.

Another reason is that our buildings have become more complex. A building in terms of a “product” can be seen as an assembly of different parts, elements and technical systems built up out of different materials. In this combination of different technical systems each of these subsystems may have different (sub)functions, but also these subsystems each can have their own Technical Service Life that often is different from other Service Lives and different from the “overall” Service Life of the building. In these systems the structure is usually the longest lasting “building layer”. [Steward Brandt 1994] already indicated the differences in these typical Service Lives of sub-systems ranging from “Stuff” to ”Structure”. Building service systems and façade systems may have a typical service life of about 15 to 30 years, structures may have service lives of 40 up to 75 years or more. Internal Layout of the space plan, formed by partition walls, may face much shorter Service Lifes, for example ranging from 7 to 15 years. In order to prevent that the building system with the shortest Service Life determines the overall Service Life of a building the building should have a sufficient level of Flexibility and Adaptability to accommodate changes and also to make it possible to replace and upgrade building elements and systems with shorter service life.

1.3 Flexibility and Adatability

Vacancy in the property market but also the need to refurbish and upgrade our existing building stock to fast changing requirements of users and occupants in virtually every sector of the building market has made us much more aware of this need towards the capacity for change, (often referred to as Adaptability and Flexibility in buildings). Our public bodies are now even required to take on an exemplary role [EU Directive 2012] in the conversion and energy upgrading of our existing building stock.

From a material point of view we need to further optimise our material resource use and decrease at the same time the burdens caused by construction and demolition (C&D-) waste. There is the need to “step up the ladder” and move from re-use at material-level towards reuse at building level. This can be achieved by focussing more at building component level or even reusing more at building and building structure level (see figure 2).

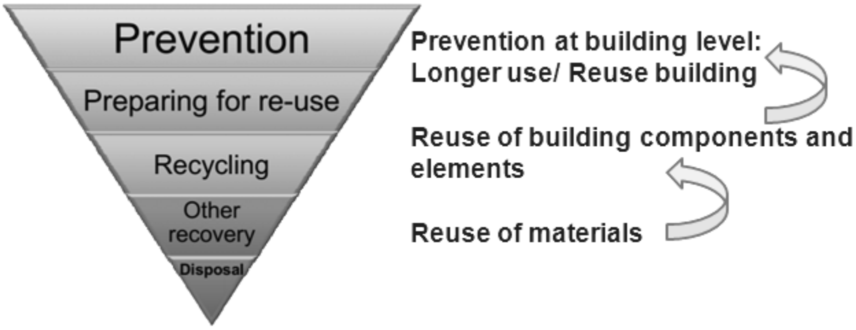


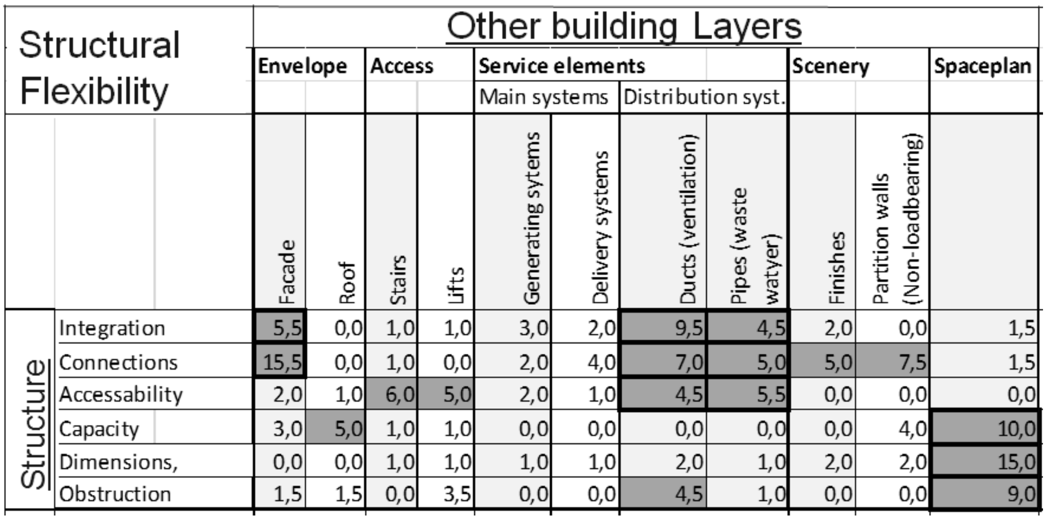
Figure 2; Ladder of Lansink (adapted) showing the preferred options for dealing with our construction and demolition waste, with a shift from materials recycling to reuse at a higher level.

Because our existing building stock makes up a large part of our society's capital, the average length of use of our building stock influences our accumulated capital. If we would be able to elongate the effective Service Lives of our built environment, (or prevent the future shortening of building Service Lives) if only by a small percentage, this would amount to a substantial figure in terms of capital, materials and potential CO2 eq reduction. Life Cycle Thinking (LCT) covering the whole lifecycle of the building, elongating service lives and closing cycles is the necessary way forward.

2 ASSESSMENT OF STRUCTURAL FLEXIBILITY

To what extend building parts, subsystems or Building Layers can be adapted and/or replaced depends on how their interactions are organised [Leupen 2002]. These relations can be evaluated on a functional, but also on a technical and physical level [Durmisevic 2006]. In this paper the assessment of these interactions and their relation to the buildings Service Life has been investigated on 18 buildings in the city of Eindhoven, Netherlands

For the evaluation and qualification of Structural Flexibility a method described in [Koopman 2010] has been used. A preliminary method [Blok 2012] that assessed the relations between the Buildings structure and its other building layers was used. The Structural Flexibility of a building is defined as the capacity of the buildings structure for changes to all other parts of the building without the need for changes to the building structure itself. The method uses a scoring matrix. Figure … shows the set up of the used scoring matrix. Properties of the Structure (vertical axis) are scored against other building layers (horizontal axis) such as Building Envelope or Building Services. The dark grey cells were selected as focus point because experts indicated these relations as more important than others [Koopman, 2010]



Structural Flexibility		Other building Layers										
		Envelope		Access		Service elements				Scenery		Spaceplan
						Main systems		Distribution syst.				
		Facade	Roof	Stairs	Lifts	Generating sytems	Delivery systems	Ducts (ventilation)	Pipes (waste watyer)	Finishes	Partition walls (Non-loadbearing)	
Structure	Integration	5,5	0,0	1,0	1,0	3,0	2,0	9,5	4,5	2,0	0,0	1,5
	Connections	15,5	0,0	1,0	0,0	2,0	4,0	7,0	5,0	5,0	7,5	1,5
	Accessability	2,0	1,0	6,0	5,0	2,0	1,0	4,5	5,5	0,0	0,0	0,0
	Capacity	3,0	5,0	1,0	1,0	0,0	0,0	0,0	0,0	0,0	4,0	10,0
	Dimensions,	0,0	0,0	1,0	1,0	1,0	1,0	2,0	1,0	2,0	2,0	15,0
	Obstruction	1,5	1,5	0,0	3,5	0,0	0,0	4,5	1,0	0,0	0,0	9,0

Figure 3; Structural Flexibility matrix with initially used structural flexibility indicators and (indicated by the numbers:) the number of times experts assessed each particular relation as important

Following this approach the Structural Flexibility of a building is here defined as the capacity of the building structure for changes to all other parts of the building without the need for changes to the building structure itself.

3 TEST RUN ON 18 BUILDINGS IN EINDHOVEN …

As a test run for further research on a bigger population now two groups of buildings (an initial total of 18 buildings) in the city of Eindhoven have been compared. In one group were buildings that have recently been demolished (or deconstructed). The other group contained buildings that have recently been reused / conversed. Figure … gives an impression of the type of buildings (multi-storey) and their Structural Flexibility assessment.

Total score	0,70	0,69
	0,69	0,01
Focus score	0,89	0,84
	0,86	0,04
Total score	0,73	0,71
	0,72	0,01
Focus score	0,80	0,87
	0,83	0,07
Total score	0,65	0,65
	0,65	0,00
Focus score	0,88	0,91
	0,89	0,04
Total score	0,65	0,62
	0,63	0,04
Focus score	0,68	0,66
	0,67	0,03
Total score	0,54	0,56
	0,55	0,02
Focus score	0,53	0,51
	0,52	0,01

Figure 4; 18 different buildings (9 reused and 9 demolished buildings) were scored on Structural Flexibility (the table shows the Total score and Focus points score by two different assessors)

Preliminary results are shown in figure 5. The structural flexibility score (both the Total Score and the Focus score) of the two groups of buildings are plotted against the Service Lifes of the Buildings. Because for buildings that have not yet been demolished because they were recently reused and conversed, a final age cannot yet be determined.

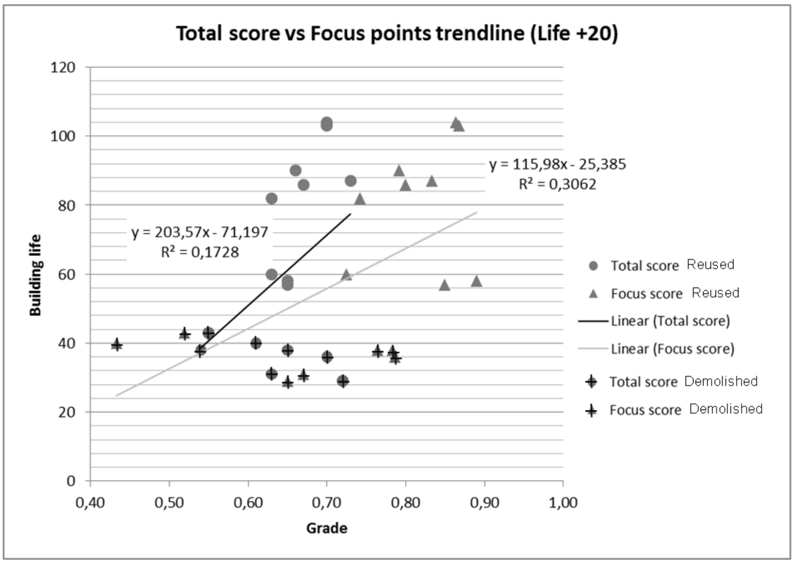


Figure 5; Graph of the aggregated Structural Flexibility score (Total and Focus points) versus the buildings Service Life.

It was for the moment assumed that for these buildings the Service Life would amount to their current age plus another 20 years after their recent conversion (+20 yrs).

Looking at the graph it can be concluded that there is no or only a very weak relation between the buildings Service Life and its Total Structural Flexibility score (round dots in the graph). For the aggregated Focus score (triangles in the graph) the correlation seems to be slightly better. However also some buildings with a higher Focus score apparently still faced early demolition. Figure 6 shows a different representation of the results. The three graphs show the calculated survival probability of all buildings (light grey triangle line), but also the survival probability of buildings with an above average Structural Flexibility (diamond shaped line) and a below average Structural Flexibility (dark square shaped line). For example, for buildings with an above average assessed Structural Flexibility, the graph shows a probability of 50 % that these buildings will achieve a Service life of 60 years or longer. For the buildings performing below average this probability falls to less than 20%. Obviously the limited number of buildings in the test and also the used preliminary character of the assessment methodology make these results not reliable. Sound statistical conclusions cannot be drawn here. This figure is shown here to give an impression of the kind of results that are sought in future research on larger groups of buildings.

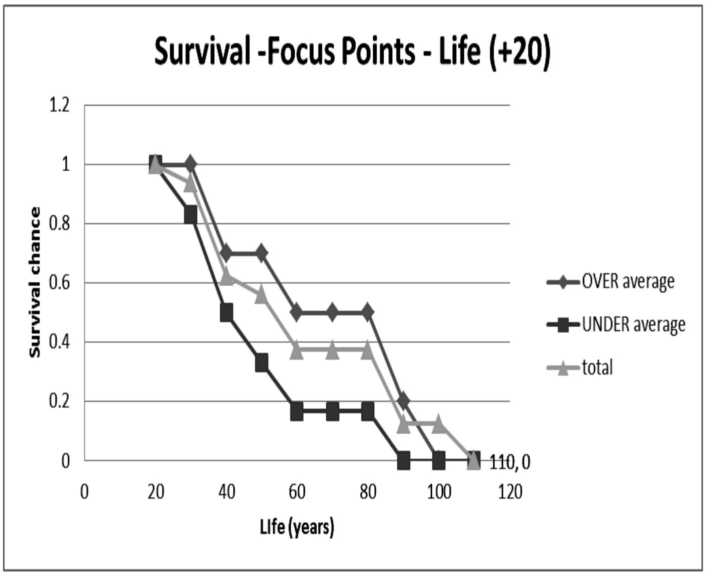


Figure 6; Survival Probability and Average life expectancy for 18 Buildings in Eindhoven compared to the life expectancy for buildings with an Over- and Under- average Structural Flexibility Score.

Other results also of future research will be the correlations between certain buildings properties and the buildings Service Life. Figure 7 shows an example of such a research result. In this case the figure plots the results (again the test run on 18 buildings in Eindhoven) of the indicator "Space Plan" and its relation to the Service Life of the Building. In this graph the crossed points represent the already demolished buildings, the grey points the re-used, refurbished or converted buildings.

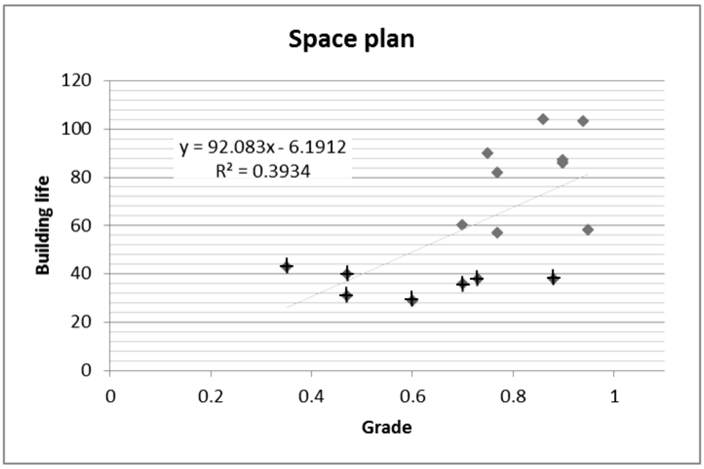


Figure 7; Building Service life versus the Structural Flexibility, Indicator Space Plan. The reused buildings are indicated in grey ,the demolished buildings are indicated with a cross.

Obviously the limited number of buildings in the test (two groups of buildings, starting out with 2x 9 buildings) and also the used preliminary character of the assessment methodology make the results so far not reliable. Sound statistical conclusions cannot be drawn here. One or two strange results can have already a large effect on calculated averages. One of the found shortcomings was that so far the Flexibility scores that were used do not use any weight factors and do not have any hierarchy. All indicators in the test ranged from 0 to 1,0 and each was given the same weight. This means that a relatively unimportant aspect had the same influence on the final score as a relatively more important factor.

4 REDEFINING THE STRUCTURAL FLEXIBILITY INDICATORS

The result of the test run indicates the necessity to again look closely at the approach and definition of the Structural Flexibility indicators. Figure 8 shows an improved and more theoretical approach to the Structural Flexibility indicators. The basis will be formed by an evaluation of Autonomy and Suitability relations of the building layer Structure with the other building layers and elements in respectively the Functional, Technical and Physical domain. If there is for example no Functional independence between the building structure and the façade (in case of a load bearing façade structure) this will be decisive. It will result in a low structural flexibility score on this relation. On the other hand if the Functional and Technical domain of the relations receive sufficiently high ratings it is expected that the physical domain, how the building layers physically come together, should be of a lesser importance on the end-scores. At the moment the buildings are being re-evaluated with this approach to see how these differences may influence the end scores. Obviously final conclusions and correlations can only be found by assessing much larger groups of buildings.

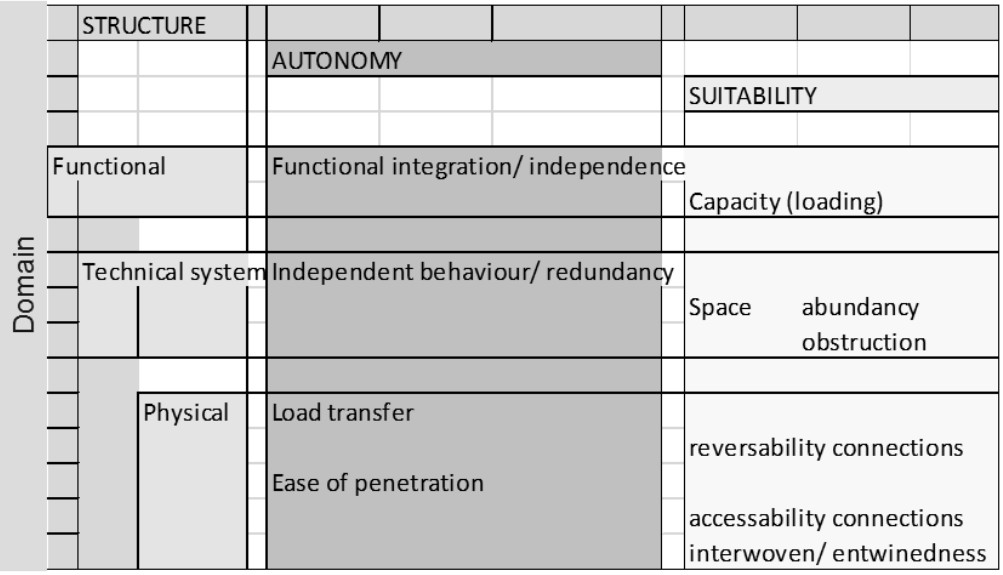


Figure 8; Theoretical framework for definition of the Structural Flexibility indicators in the functional, technical and physical domain.

5 CONCLUDING REMARKS

To improve accuracy in Sustainability assessments of buildings it is necessary to come to improved Estimated Service Lives of buildings. Because the functional Service Lives of Buildings is becoming more important it is necessary to further research the relation between the life expectancy of buildings in terms of its “Functional Service Life” and the buildings “Structural Flexibility”. From the first results of the test run it seems possible to assess and score Structural Flexibility of Buildings. The first test on the 18 buildings indicates that there might be a relation between the structural Flexibility and the Functional Service lives of Buildings. Some correlations however are still rather week. The used methodology of the flexibility indicators needs further improvement. Hierarchy and introduction of weight factors can improve the correlation. For this also the number of buildings in the assessment needs to increase. In doing so it is expected that (key-) properties of a buildings structural configuration on a functional, technical and physical level (together the buildings Structural Flexibility) and their influence on the life expectancy of buildings and with that possibilities to achieve an improvement in the Estimated Service Life of buildings can be found in more detail.

REFERENCES

1) Blok, R. Herwijnen, F. van. 2006 *Quantifying Structural Flexibility for performance based life cycle design of buildings.* Proceedings international conference Adaptables ‘06, volume 1, Eindhoven

2) Blok, R. Gervásio, H. 2007 *Criteria for sustainable construction*, Proceedings Workshop Sustainability of Constructions, cost action C25, Lisbon.

3) Blok, R. e.a., 2011 *Case Study Virtual Office Building II*, Integrated Approach to Life-time Structural Engineering, proceedings Cost action C25, Sustainability of Construction Volume 1, p 429-445

4) Blok, R e.a. 2012 *Structural flexibility in relation to integrated service life design of buildings,* proceedings IALCC congress, Vienna

5) Brand, S. 1994 *How buildings learn*, New York, Viking/ Reed / Penguin Books

6) CIB W080, Hovde, J. Moser, K 2004, *Performance based methods for service life prediction*, publication 294 CIB, Rotterdam

7) CML 2001, *Life cycle assessment (LCA), An operational guide to the ISO standards*, Centre of Environmental Science Leiden University (CML) 2001

8) Durmisevic, E. 2006, *Transformable Building Structures*, PhD Thesis, Delft University

9) EU Directive 2012, *European Commission EC, Directive 2012/27/EU on energy efficiency*, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC

10) Hoekman, R.W.J. Blok, R. Herwijnen, F. V. 2010, *A neuro-fuzzy knowledge Model for the quantification of Structural Flexibility*, Eindhoven University, Netherlands

11) Hoogers, J. 2004, *Bouwen met Tijd*, (In Dutch) S.E.V. Rotterdam, Netherlands

12) ISO TC59 2008, *ISO 15686-1-6 Buildings and constructed assets; Service life planning,* ISO International Organization for Standardization

13) Koopman, E.F. 2010 *Inventarisatie en kwanlificatie van Flexibiliteit* (In Dutch), Msc thesis, Eindhoven University

14) Leupen, B. 2002, *Kader en generieke ruimte* (in Dutch) 010 publishers,Rotterdam

15) Nunen, H. v. 2010, *Assessment of the Sustainability of Flexible Building,* Aeneas, Boxtel, Netherlands