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Developing adaptability indicators for high-rise buildings

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1. INTRODUCTION

With the goals of the Dutch government to reach a complete circular economy by 2050, the building and construction industry seeks ways to shift towards a circular sector. Additionally, the ratio of urban:rural population worldwide has been increasing, which is also notable in the Netherlands [1]. Since the horizontal space in the Netherlands is scarce, vertical expansion is a solution to increase space. Future high-rise buildings should follow the circularity goals by the Dutch government and should be designed and constructed in a circular manner.

A large number of high-rise buildings have been voluntarily demolished, while they had not yet reached their end-of-life stage [2]. Preliminary demolition is mainly to create space for new buildings, with improved technologies or other functions. To discourage the demolition of high-rise buildings, one could implement the Design for Adaptability circularity strategy. This strategy aims to design a building that can be easily adapted, so that reuse of the building is more likely.

One of the main challenges in the implementation of Design for Adaptability is the lack of an adaptability indicator. Existing methods of measuring circularity either focus on the material loop (e.g., the Material Circularity Indicator proposed by the Ellen MacArthur Foundation [3]) or omit adaptability (e.g., the Building Circularity Index proposed by Verberne and Teunizen [4; 5]). Therefore, it is difficult for structural designers to convince clients of the benefits of adaptability. Besides, current research focuses on how adaptability can be achieved in the architectural domain [6]. The structural domain has not been widely investigated, especially that of high-rise buildings.

In this research, two adaptability indicators that operate on the building level are proposed in Section 2. In Section 3, the indicators are applied to two high-rise buildings. The effects on the material use by using Design for Adaptability are further discussed followed by the conclusions in Section 4.

2. ADAPTABILITY INDICATORS

Researchers have tried to formulate factors which influence the adaptability of a building. Rockow [7] investigated various factors including: reserve capacity, quality materials, floorplan openness, floor-to-floor height, simple design, separated layers, and accurate plans. Platform CB'23 identified modularity, grid size, simplicity, reserved capacity, floor-to-floor height, recess flexibility, disassemblability, capacity installations, separation of layers [8]. After interviewing structural designers in practice in the Netherlands, we locate three factors that are of great importance in measuring adaptability in the structural domain, i.e.: openness, reserved capacity (foundation and floor) and floor-to-floor height.

Function Adaptability Indicator (FAI). The FAI represents the possibility of accommodating different building functions (gathering, prison, healthcare, industrial, office, lodging, education, sport, shopping, and residential). Each building function has different requirements on the properties of openness, reserved capacity, and floor-to-floor height. For example, a healthcare function is not possible when the module has a small floor-to-floor height or a low load capacity, due to the requirements from heavy equipment. The FAI is calculated as $FAI = \sum_1^n WF_i$, where n is the maximum number of available building functions. WF_i is the weighting factor for function i, which is calculated based on the property value and total area of building function i in the Netherlands:

$$WF_i = a \cdot (V_{p,i} / V_{p,tot}) + b \cdot (A_i / A_{tot})$$

Where:

a	=	Factor property value
$V_{p,i}$	=	Property value for building function i
$V_{p,tot}$	=	Total property value
b	=	Factor area
A_i	=	Area of building function i in the Netherlands
A_{tot}	=	Total building area in the Netherlands

Table 1. Property value of building functions. Source: The Benchmark Municipal Real Estate [9] & Niessink et al. [10].

Building function	V_p [€/m^2]	A [10^6 m^2]	WF_i
Gathering	1050	35	0.07
Prison	900	5	0.06
Healthcare	1300	40	0.08
Industrial	750	265	0.08
Office	1100	90	0.08
Lodging	2100	20	0.13
Education	1150	35	0.08
Sport	750	15	0.05
Shopping	2300	55	0.15
Residential	1700	905	0.23
TOTAL	13100	1465	1.00

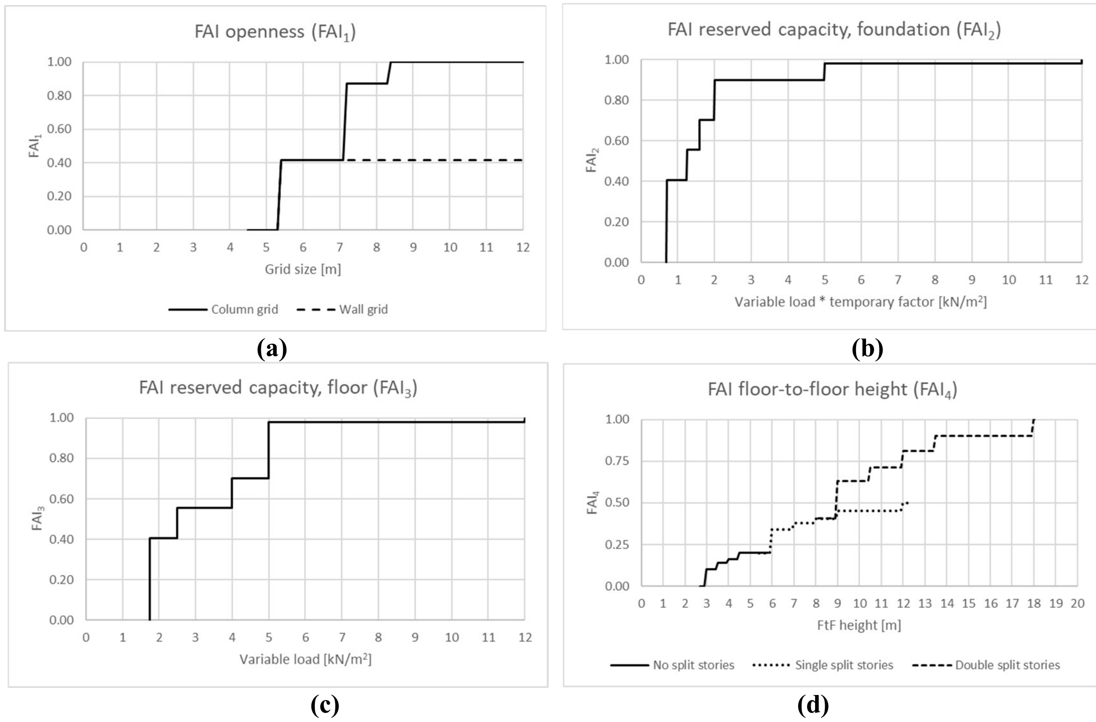


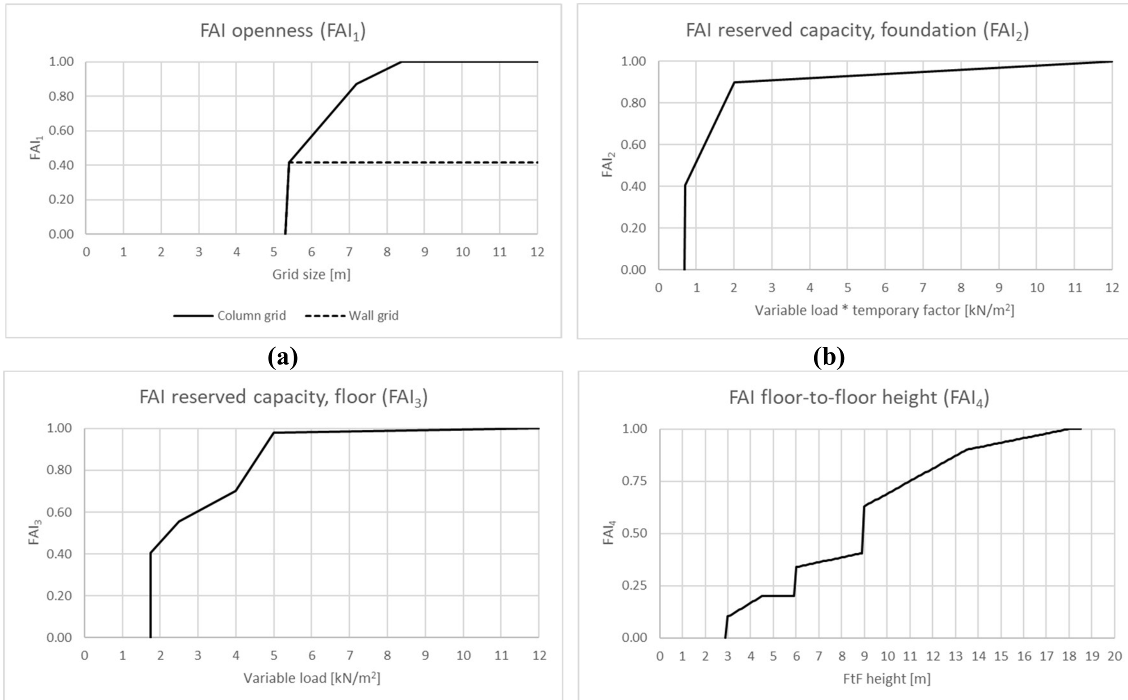
Figure 2. Relation between FAI and design factors a: Openness ; b: Reserved capacity foundation ; c: Reserved capacity floor ; d: Floor-to-floor height.

When a new building function is possible in the module, the FAI increases with the weighting factor of that function, as is illustrated in Figures 2a-2d. Each newly available function results in a jump to a higher FAI. For example in Figure 2a, at a grid size of 7.2 meters, five new functions become available in the module, namely gathering, healthcare, office, education, and shopping. This results in the large jump at 7.2 meters in the FAI for openness, namely from 0.41 to 0.87.

In Figure 2a, the value of FAI makes a distinction between using a column grid and a wall grid, where the wall grid can only accommodate a prison, lodging, or residential function. This is because in practice, it is not realistic to realize the other building functions with a wall grid, which typically gives a less open structure.

In Figure 2b and 2c, the value of FAI is split in the floor load capacity and foundation load capacity. In Figure 2d, the value of FAI depends on the possibility of splitting the story, where either one floor is added halfway, or two floors at one- and two-thirds respectively. The availability of splitting stories results in a significant increase of the FAI, which can be observed at a floor-to-floor height of 6 meters for a single-split story, or 9 meters for a double-split story.

The adaptability of a module does in practice not increase by intervals, but in a ‘smooth’ manner, because a new function can also be possible just before the jump. By smoothing out the FAI interval graphs of Figures 2a-2d, the final FAI for each sub-indicator is obtained, which are depicted in Figures 3a-3d.



(a) (b) (c) (d)

Figure 3. Smoothened FAI for a: Openness ; b: Reserved capacity foundation ; c: Reserved capacity floor ; d: Floor-to-floor height.

Design Adaptability Indicator (DAI). From a structural designers' point of view, it is interesting to obtain a single adaptability indicator to be able to quantify the adaptability of his building design. They could use this information to prove what level of adaptability can be achieved with (a combination of) certain design actions. Therefore, this research proposes the DAI, which is a more abstract indicator that indicates adaptability in a more general sense as opposed to the FAI. To obtain the DAI for a building, the FAI's are combined by using weighting factors, based on the interviews with structural designers, resulting in the DAI:

$$DAI = \sum_{1}^{4} FAI_j W_j$$

Where:

FAI_j	=	FAI of design factor j
W_j	=	Weighting factor for design factor j

Table 2. Sub-indicators FAI_j with corresponding weighting factors.

Design factor j	*Sub-indicator*	W_j
Openness	FAI_1	$W_1 = 0.35$
Reserved capacity ; foundation	FAI_2	$W_2 = 0.15$
Reserved capacity ; floor	FAI_3	$W_3 = 0.10$
Floor-to-floor height	FAI_4	$W_4 = 0.40$

The FAI's are linearly combined into the DAI, which means that a building with a large FAI_{1-3}, but a low FAI_4, could still result in a high DAI. However, a low FAI_4 means that a low, non-adaptable, FtF height is chosen, which in turn means that the number of building functions that can be adapted to is limited. Therefore, the DAI does not necessarily tell something about the number of functions that a building can be adapted to. This is only the case for the FAI's. The DAI rather provides an indication of a building's adaptability in a more general sense. More discretely this means that the DAI provides an indication of the possibility that a building is reused, not the possibility of adapting to a certain function.

3. CASE STUDY

A case study on a high-rise building with a maximum height of 100 m is performed. The case study investigates the material use of two designs: design A and design B. Design A is a building that has typical structural properties of a residential high-rise building, which means it has a small grid size, load capacity, and FtF height. Design B is a building that follows the same structural principle as Design A, but with increased values of the grid size, load capacity, and FtF height. The properties of these variants are shown in Table 3. For both variants, a structural analysis is performed to determine the dimensions of the structural elements. The structural analysis includes the variable floor load and self-weight of the structural elements. The resulting values of the adaptability indicators are shown in Table 4.

Figure 4 shows the comparison of the structural analysis results of Design A and B. For building B, a distinction is made between using a floor-to-floor height of 6 meters or splitting the story and using a floor-to-floor height of 3 meters. In the latter, removable floors are used to be able to switch towards 6 meters and maintain a high adaptability.

Table 3. Properties of design variants.

	Design A	*Design B*
Building dimensions	25.2 m x 36.0 m	25.2 m x 36.0 m
Building height	99.0 m	96.0 m
Stability system	Core	Core
Material	Timber (core in concrete)	Timber (core in concrete)
Floor system	Kerto Ripa	Kerto Ripa
Building function	Residential	Industrial
Number of stories	33	16
Grid type	Column grid	Column grid
Grid size	5.4 m	7.2 m
Variable load	2.55 kN/m^2	5.00 kN/m^2
Temporary load factor	0.4	1.0
Floor-to-floor height	3.0 m	6.0 m

Table 4. Adaptability Indicators for designs.

	Design A	*Design B*	*Difference*
FAI_1	0.41	0.87	+ 112%
FAI_2	0.41	0.93	+ 127%
FAI_3	0.56	0.98	+ 75%
FAI_4	0.10	0.34	+ 240 %
DAI	0.30	0.68	+ 127%

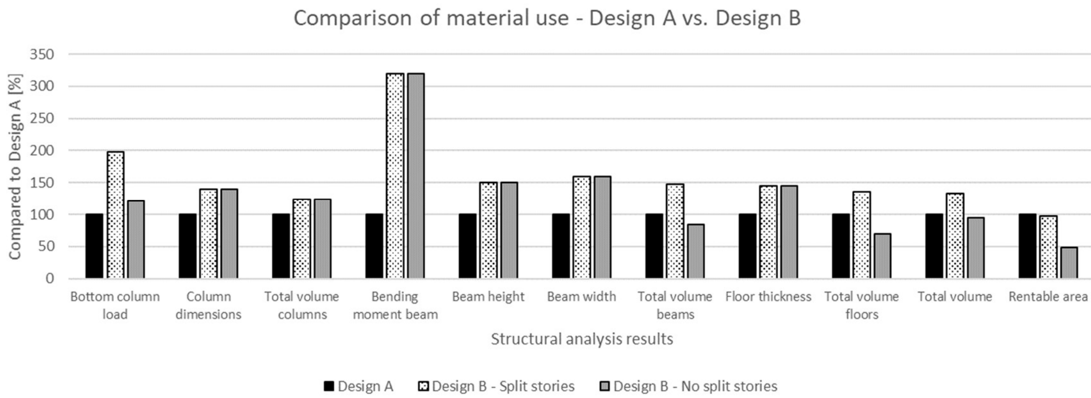


Figure 4. Comparison material use between Design A and B, normalized such that Design A is 100%.

Figure 4 shows that the loads in Design B are larger. For example, the bottom column load is 21% larger in the variant without split stories and 98% larger in the variant with split stories. This leads to a 40% increase in the column dimensions compared to Design A. Because Design B has less stories, its total volume of structural materials is also lower, even though its element dimensions are larger. The downside of this is that more than half of the rentable area is sacrificed when split stories are not used. Finally, from Table 4 it is seen that Design B has significantly increased functional flexibility as indicated by the large increase of the FAI's. Additionally, the DAI is increased by 127%. Relative to the increase of the material use, the adaptability of Design B is greatly improved.

4. CONCLUSION

In this research, a new indicator is created to measure the adaptability of a building: the Function Adaptability Indicator and the Design Adaptability Indicator. The quantification of adaptability will lead to a more stable basis to implement the Design for Adaptability strategy, to prevent demolition. This can be done by measuring functional flexibility through the FAI's or through measuring adaptability in its general sense through the DAI. By performing structural analyses and using the adaptability indicators, it is proven that it is possible to increase the general adaptability of a building with 127% at the cost of merely 33% extra material use. Therefore, the increase of the material use is not significant compared to the increase in adaptability for a high-rise building. Concluding, by constructing the adaptability indicators, it is shown that with little investment of materials a large adaptability and functional flexibility can be achieved.

In future research, it is recommended that the study on a the adaptability indicators is further elaborated by implementing them in a large data set of buildings. This could provide insight into the correlation between the probability of demolition of a building and its adaptability, which can be used to further improve the accuracy of the FAI's and the DAI.

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