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Expanding Boundaries:
Systems Thinking for the Built Environment

HOLISTIC OBSERVATIONS ON THE SUSTAINABILITY OF HIGH-RISE BUILDING FAÇADES

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Abstract

High-rise buildings are currently experiencing a renaissance in Switzerland. The building element with the largest surface area of this omnipresent building type is its envelope, which on average makes up 20-25% of overall construction costs. At that complex interface between the interior and exterior, almost all planning parameters meet with constantly growing demands. Based on 14 current high-rise façades, an interdisciplinary research team from the HSLU T&A [1] developed content-based principles for a decision making instrument [2]. The CTI-Project “Building Envelope” focuses on the following question: Which decisions are made by an investor in early conceptual and planning phases when it orders a sustainable building envelope for a high-rise building, and which effects do those decisions have on the economy, ecology and society? The project generates and communicates knowledge of the highly complex connections and interactions in producing a building envelope for multi-storey buildings. Available analysis data in the system of the EAK/OAK [3.] allows its direct integration into working tools for the building industry provided by the CRB [4.].

The research project shows the leverage effects of the most important decisions and their effects on the sustainability of high-rise building façades, whereby the insight can also be adapted to conventional building envelopes.

The developed matrix presents connections with respect to façade typology, the number of layers of transparent building elements and building utilisation. The relevant systems are assessed and viewed in relation to each other. Firstly, the project demonstrates the considerable influence of early planning decisions such as geometry or the construction using a created economic model. Secondly, a comparison between chosen reference sections shows that the structural details of the building elements and their cybernetic mode of action are decisive for the life-cycle of the building envelope. Buildings only become entirely sustainable with as long of a utilisation period as possible.

Keywords:

Sustainability of high-rise façades; life-cycle observations, sustainable envelope; decision making instrument

1 INTRODUCTION

1.1 Building envelope interface accumulation

Like human skin, the building envelope is a highly central and complex “organ”. Unlike the classic façade, it three dimensionally surrounds the entire building volume including its underside, façade and roof and is therefore a building element that covers an extensive area. It serves to mark the boundary between the interior and exterior, with all the significance, requirements and values that that entails. The building envelope plays a central role in connection with the energy demands of various labels. It is responsible for fulfilling daylight requirements, transmission losses, solar gains, etc. In view of today’s and future requirements, the building envelope represents a growing investment factor

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with respect to the facility's costs [5]. At the same time, in addition to power generation and building technology, it also represents a significant factor in the ecology of a building, in its capacity as a central grey energy factor and with respect to operative and maintenance costs, thereby representing a large proportion of the overall building system [6]. Today, life-cycle costs are often underestimated compared to production costs. In the planning and building process, the building envelope represents the "building site" with the highest complexity and interdisciplinarity. At that boundary, almost all fields of planning meet. In the building process, it also forms an accumulated interface between the different trades. As is known, the challenges of planning, logistics and the building site lie in those interfaces and their localisation and solution.

1.2 Focus on high-rise buildings in Switzerland

In Switzerland, tall buildings in general are the subject of heated debate in view of the demand for densification, both in the context of preserving the character of locations and also with respect to their architecture. The labels and the Swiss aims of quality in architecture and their implementation represent a unique characteristic that justifies currently limiting the research project on high-rise buildings [7] to Switzerland.

1.3 Underlying question

How can a sustainable building envelope be ordered and which influencing factors must be taken into account at an early planning stage? Practical experience shows that most clients and also planners are not completely aware of the complex interconnections and interactions.

The research project offers as comprehensive, valued and synchronized assessment order for possible questions and solutions with respect to decisions on a sustainable building envelope at an early planning stage.

2 METHODS

2.1 Terms and typologies of building envelopes

In the CTI-project "Building Envelope – A tool for decision making and assessment to produce sustainable façades for multi-storey buildings", 14 high-rise building façades were analysed and assessed with respect to their ecological, economic and social effects.

The term building envelope is suitable to describe an uninterrupted protective layer on all sides and includes the horizontal surfaces such as roof areas and undersides of that building element. Highly contrasting definitions are circulated with respect to the typologies of building envelopes. To grasp this great spectrum using uniform terms, the following matrix is developed (Fig.1):

- Primarily, the transparent building elements are relevant to energy requirements (solar gains, transmission losses, sun protection, sound insulation, etc.). The layers of the building shell on a horizontal plane play a primary role. One can distinguish between single or double-layered open and closed building envelopes (CCF).
- The building envelope can never be entirely uniform, since there are always interfaces between the respective façade and rooftop surfaces. Subsumed beneath edges, there are mountings and bonds. The relationship between the shell construction and the number of bonds generates the typologies of all-sided (punctuated façade), lintel and parapet (band façade), and roof and base (curtain wall).
- A further characteristic, the expression of the exterior opening structure, plays a significant role (not shown in the simplified matrix Fig.1). To differentiate the 2nd axis in Fig.1, a hole-shaped expression both with a conventional punctuated façade and as a curtain wall (e.g. Hochhaus Hagenholz) was created. But there

Fig. 1: Typology of the building envelope.

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are considerable differences in terms of building technology (weight, assembly, building progress) that have economic consequences for the two construction methods.

The typologies **layers** and **edges** are presented as a diagram with two axes as seen in Figure 1.

2.2 Building quantity structure

The analysed buildings vary greatly in assessing their quantities. The volumes (GV) range from the smallest building's 40,000 m^3 to the largest building's 420,000 m^3. Overall, an extended quantity structure in accordance with SIA 416 analysed more than 380 storeys. The floor spaces (GF), with areas of 13,000 m^2 to 81,000 m^2, make up a factor of 6.2. If one considers the relationship between the exterior envelope of the building to the floor space, the result is a proportion of 18% to 60% > factor 3.3 (cf. Fig. 2):

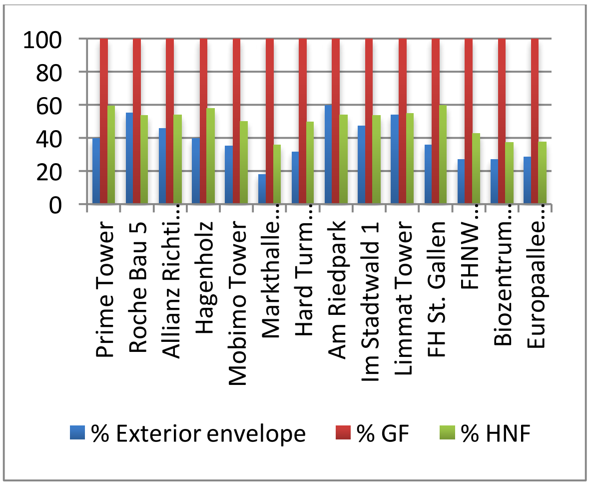

Fig. 2: Exterior envelope % (eBKP-H; E) to floor space % (=GF) and main usable area % (=HNF) to SIA 416.

Economic model in accordance with CRB standard eBKP-H/2012

The CRB standard "eBKP-H/2012 Baukostenplan Hochbau" forms the basis of analysis. That classification describes the costs for the production of a building. The volumes and uniform prices have been produced for all façades according to the bottom-up method on the level of building elements. In the supplementary facility and construction costs, all volumes of the building were classified using model calculation (eBKP-H main groups A/B/I/V/Z) and individual calculation of the building envelope (main groups C/D/E/F/G). The comparability of the buildings is therefore ideal. In Fig. 3, the costs are derived as Fr./m^2 of the façade system E2.4 (eBKP-H) or the building envelope (façades above ground including roof). If the costs of the building envelope are combined with the geometry (GV/HNF), however, one finds the enormous influence of the quantity structure on the materials and their costs. The leverage effect of the geometry or its appropriateness is almost 50% of the building envelope and defines up to 23% of the facility costs.

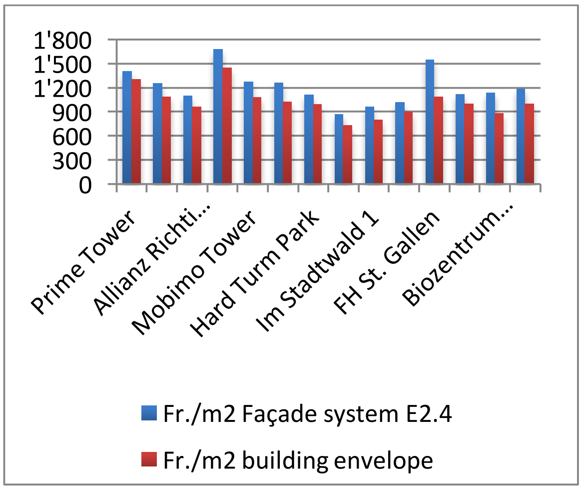

Fig. 3: Fr./m^2 Façade system and building envelope.

2.3 Reference section, module size and construction procedure

Figure 4 demonstrates the diversity of the reference sections. Some of the façade sections differ considerably in terms of their module size of 4.52 m² to 31.51 m². All sections remain room-high however and vary between 2.86 m and 4.52 m in height. In terms of their breadth, the modules vary from 1.35 m to 7.05 m.

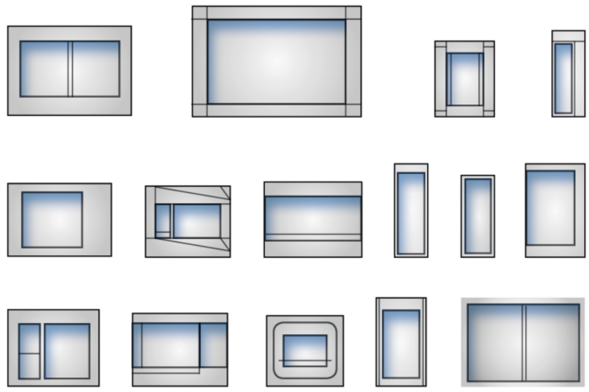

Fig. 4: Collected reference sections as a "façade zoo" without hierarchy.

2.4 Life-cycle assessment of a section in detail

The lifespan of the relevant building elements was determined using planning documents on a scale of 1:2 to 1:5. Rather than the material-related lifespan, it was the constructive study in detail that was decisive in the assessment of maintenance, renovation and dismantling. These key figures of life-cycle assessment over a period of 90 years formed the basis a holistic assessment of the sustainability of the high-rise building façades.

2.5 Qualitative factors

During the project, the IFZ studied the extent to which qualitative factors have an effect on the commercial success of an object. The project used two instruments for this purpose:

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- A typology grid with respect to the building envelope, as a communication tool among experts, working with pairs of terms.
- The "QualiTool" developed by the IFZ to identify and quantify the quality in the sense of effectiveness in achieving the intended targets, in an analogous way to the SNBS procedure.

2.6 Life-cycle costing (LCC)

In an increasingly ecologically-orientated real estate economy, the process of life-cycle costs is accepted due to its holistic perspectives. Its inclusion in operative and disposal costs allows the principle of sustainability to be applied, since sustainability considerations often lead to lower operative and maintenance costs. Relevant concepts especially include studies by IFMA [9], CRB [10] and the SIA [11].

2.7 Levels of comfort

The assessment of levels of thermal and visual comfort was defined in five different categories (see Fig. 5: daylight, sun protection control, summer heat protection, cold air drop, openable windows) and implemented according to clearly defined criteria by the Centre for Integrated Building Technology ZIG. The categories cannot be compared to each other directly. Thus, the final result is presented in a qualitative assessment in point scores.

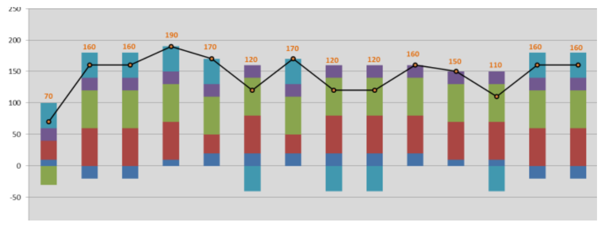

Fig. 5: Façade comfort level assessment. The leverage effects can be positive or negative depending on the assessment criteria. The façade design is strongly dependent on the relevant typology and use.

2.8 Life-cycle balance

The life-cycle balance of a high-rise building façade was defined by the quantity structure of the building envelope multiplied by the environmental factor of the individual building elements (UBP, grey energy, CO_2 emissions) [12], [13], [14]. As a rule, two comparative values were used in assessing the façades: The life-cycle balance of the added building materials added at the time of the high-rise building's construction without taking their intended use period into account, i.e. the life-cycle balance in Year 0 (without amortisation), and the life-cycle balance per year (with amortisation).

2.9 Energy requirements

Using thermal simulations (IDA ICE 4.2) the ZIG determined the energy requirements for heating, cooling and lighting of four reference buildings and compared them with the energy reports of all buildings in accordance with SIA 380/1. The actual energy requirements of the building strongly depend on its users. There is a considerable savings potential through appropriate operative optimisation.

2.10 Qualitative guidelines for planning high-rise building façades

The Competence Centre for Façade and Metal Construction CCFM developed a qualitative assessment method to determine the following sustainability criteria: raw material origin, dismantling ability, effects on the micro-location, quality of the building structure, and façade weight. All reference sections were comprehensively assessed using a system catalogue of 22 building groups with 134 sub-categories.

3 RESULTS

3.1 Decisive leverage effects on producing a sustainable building envelope

The results of the CTI-Project "Building Envelope" show that the location and specific situation have the greatest effect on the building (cf. Fig. 6). The local conditions are decisive for the utilisation potential. The building is defined by its context and the legal stipulations. The greatest lever is defined as the **location**.

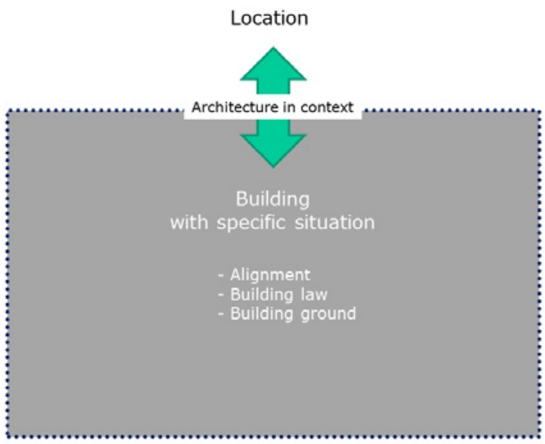

Fig. 6: Architecture as the interface between the location and the building.

The architecture acts as an interface between the location and the **building** with its specific situation in a historical, cultural, climatic and material-related context. On that level, the standard (quality) is determined with a direct influence on the costs. To assess the sustainability of the buildings, it was necessary to study the entire building. The volume of the building is formulated by the function and its use, while it expression is closely related to the façade typology. The leverage effects of the building envelope are therefore much more far-reaching in the building than the assessment of a 30-40 cm enveloping layer.

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Based on these fundamental findings, **building utilisation** is considered to be decisive (Fig. 7). On the same level, the **identity** and **atmosphere** are considered to be significant. This may either be identification through a distant effect or through the component of the acceptance of buildings or building elements at close proximity. In each case, in addition to the purely functional utilisation period, **acceptance** and **comfort levels** play a decisive role for the lifespan of the building.

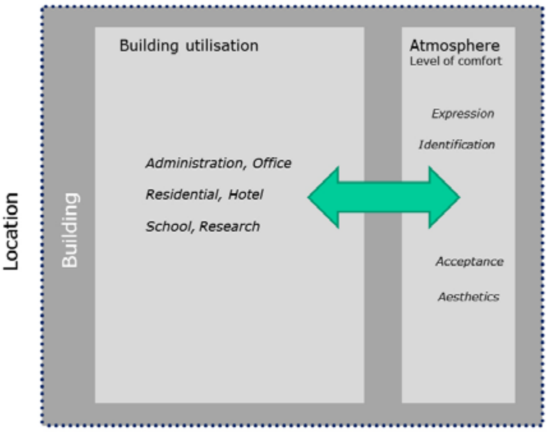

Fig. 7: Building use as a significant leverage effect in connection with the identity and expression of the façade.

The umbrella term of **geometry** comprises the following key leverage effects:

Volumetrics

- The compact nature of the building is decisive for the volumetrics; the volume is the greatest lever for production costs. On average, the building envelope makes up 20-25% of the overall construction costs (according to eBKP-H, main group C-G), while the exterior wall layer (E) is clearly the relevant main group of the building envelope, explicitly the façade system E2.4.
- On average, the construction C is responsible for 10-20% of the production costs.

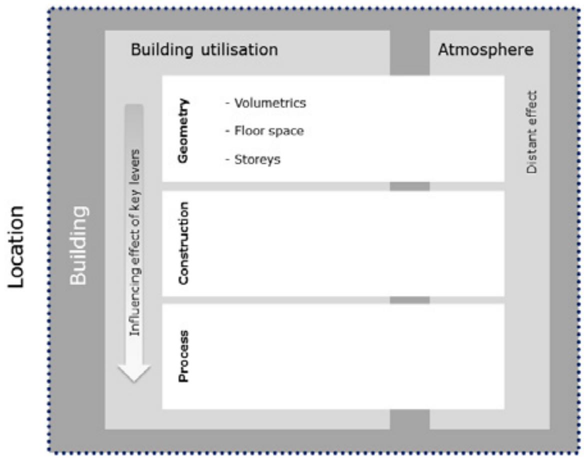

Fig. 8: Volumetrics, floor spaces and storeys as leverage effects of geometrics.

Floor spaces

- Depending on the spatial efficiency, the proportion of main usable area (HNF) to the floor space (GF) is 35-65%. The efficiency of the floor space is very important; offices and administrative buildings should aim for 60%.

Storeys

- The relationship between storey heights (OK/OK) and clear room height depends on other levers such as the envelope area. The multi-surface proportion of the façade should not be underestimated, which is necessary above suspended ceilings and doubled floors.

Another umbrella term is introduced with **construction**:

Elementation, layering, joining

- The façade typology is subject to various types of interaction, with clear relevance of the transparent (glazing) elements. The possible classification into single-layered and double-layered building elements and punctuated façades and curtain walls is reflected in all final reports by the departments.
- With respect to the principle of the primary structure, flexibility during the entire lifespan is significant for the sustainability of the building and building envelope.
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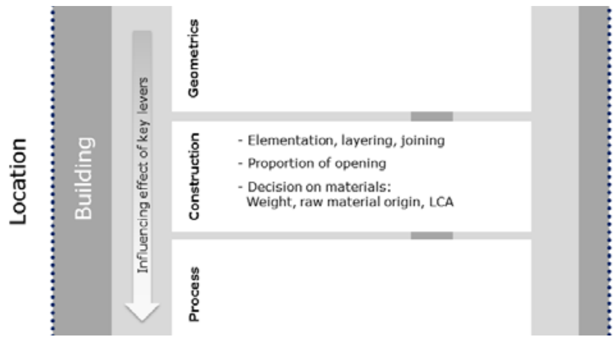

Fig. 9: Elementation/layering/joining, proportion of opening and decision on materials as leverage effects of construction.

Proportion of opening

- The proportion of opening is highly relevant to the level of comfort; it includes the factors openable windows, cold air drop, summer heat protection, daylight and life-cycle balance.
- In this context, the question of the complexity of the building envelope and the level of technology in connection with the building technology arises. Viewed over the entire life-cycle, a simple building system is favourable.

Decision on materials

- The decision on materials affects the weight of the façade and the life-cycle balance and is

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closely linked to the identification of the building.

- The choice of materials allows raw materials to be used that come from sustainable, regional production, whereby specifically in façade construction, the option of a local, regional and international origin for raw materials is often difficult to apply. Most façade building elements such as glass, aluminium profiles, natural stone etc. are produced in neighbouring countries rather than in Switzerland.
- The frame element is extremely important for the grey energy and environmental impact points (UBP 2006, Vers. KBOB 2014). Curtain walls have significantly higher values than punctuated façades. But in this respect detail is also relevant, e.g. the façade of the Biozentrum Basel (double-layered closed cavity façade) has a very positive result due to the element's low frame proportion and large-scale glazing proportion.

The umbrella term **process** for further leverage effects:

Planning and building site logistics

- Scheduled planning should be defined in a project-specific way and is highly significant for the entire process. The level of prefabrication varies greatly as a result. The construction method of the façade and façade system is relevant to the building process.

Assembly, dismantling, recycling

- Complicated constructions such as structural glazing bonds or heavy cladding and their mountings have a negative effect on the sustainability of the façade with respect to the ability to dismantle them.
- Metal building façades are generally easier to dismantle, while curtain walls produce comparatively better results.
- The specific details and their components are relevant to simple assembly, dismantling and recycling.

Processing and finishing quality

- The quality of the processing and finishing is decisive for the functional utilisation period of the façade and the building element. A decisive component for the lifespan is the acceptance of buildings and building elements over a long utilisation cycle and its identification in a close-up effect.
- According to the DCF method, it is mainly the production costs that are relevant in observing the façade, whereby the constructive details and their joining, rather than primarily the material, are decisive for the utilisation period.

Maintenance (cleaning, operation)

- The costs for maintenance and renovation including dismantling play a subordinate role in the present value observation of 60 years for the façade. This however results from the interest rate and the defined long period of observation for the maintenance in applying a dynamic calculation method of the DCF process *(IFZ report, 2.5.2014).*

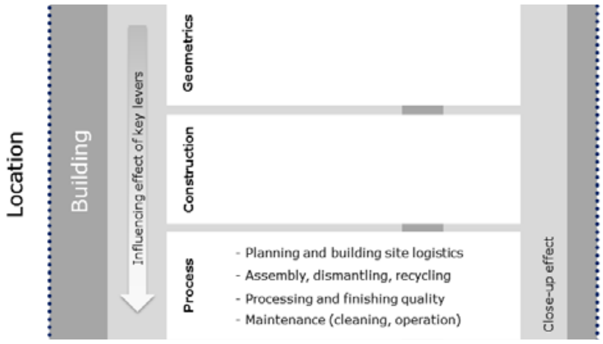

Fig. 10: Planning, assembly, processing and maintenance as leverage effects of the process.

4 DISCUSSION

4.1 A cross-comparison of high-rise building façades in Switzerland

To identify the key leverage effects to determine sustainability, it was necessary to move away from individual buildings and examine the test series buildings in a cross comparison (cf. Fig. 4 Reference sections). The selected 14 buildings in the CTI-project "Building Envelope" all achieved a very high standard, which is mainly ensured through architectural competitions and public debate. Another contributing factor in addition to the excellent quality is that tall and high-rise buildings are like the Formula 1 of the building industry. That means that the highest technical and structural requirements must be fulfilled in every respect. The comparison is therefore like a high-end test run of different building envelopes with a high public profile, not only in terms of their presence. The fact that many high-rise buildings are produced by private investors means that often diverging development steps are not revealed with respect to planning and building processes. The knowledge gathered by individual major investors based on many years' experience is generally not divulged to the public for reasons of competition. The role of the investor is decisive.

The CTI-project "Building Envelope" could however achieve a typological comparison due to the availability of extensive planning material and figures going down to in-depth detail. The produced diagram (Fig. 8 to 10) presents the decisive 10 substituent leverage effects to produce a sustainable building envelope in early planning stages as a guideline.

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5 CONCLUSIONS

5.1 Findings

The findings of the research project can also be adapted to conventional building envelopes:

- The building envelope has a considerably more far-reaching effect than the exterior layer.
- Buildings only become entirely sustainable with as long of a utilisation period as possible.
- Viewed over the entire life-cycle, the constructive detail of the building element is decisive.
- The cybernetic mode of action of the overall system plays a key role for sustainability.

5.2 Outlook

The findings of the CTI-project "Building Envelope" should lead to the further development of the eBKP-H structural system through different hierarchies of the element structure as part of a follow-up project with the CRB (Swiss Research Center for Rationalization in Building and Civil Engineering) and participating economic partners. The aim is a statement on the overall costs of the building envelope (façade and roof) including the façade scaffolding, the proportional construction and the technology. A new factor is the full costing of the building envelope, taking life-cycle costs into account. Within the overall structure, the proportion of the building envelope will be determined. In this way, the relationships and figures of all themes and stages can be inferred. The comparison of different versions of building envelopes and their consequences thereby becomes coherent. Another new aspect is the observation of the utilisation funding per m^2 main usable area (HNF), subdivided into the following three sections: overall, building envelope proportion, and façade system proportion. The effects on the main usable area decisively take the utilisation period of the life-cycle into account. This further development of the construction cost plan eBKP-H would enable the integration of economics into the gained findings of the departments ZIG and CCFM and the implementation of calculation tools.

6 COAUTHORS AND RESEARCH TEAM

Lucerne University of Applied Sciences and Arts – Engineering & Architecture (HSLU - T&A), Materials and Structure in Architecture FG MS A

Prof. Dieter Geissbühler, Dr. Alexandra Saur (Admin. management), Marvin King (Content management), Stefan von Arb (Economics)
Report: "Geometry, construction, costs" (Geometrie, Konstruktion, Kosten).

HSLU - T&A, Center for Integrated Building Technology ZIG

Prof. Urs-Peter Menti, Gianrico Settembrini, Diego Hangartner
Report: "Comfort levels and life-cycle balancing of high-rise façades" (Behaglichkeitsbeurteilung und Ökobilanzierung von Hochhausfassaden).

HSLU - T&A, Competence Center Façade and Metal Engineering CCFM

Prof. Dr. Andreas Luible, Thomas Wüest
Report: "Qualitative guidelines for planning high-rise façades" (Wegweiser für die Planung von Hochhausfassaden).

HSLU - Economics Department, Institute of Financial Services Zug IFZ

Prof. Dr. Markus Schmidiger, Andreas Binkert
Report: "Soft influencing factors on the building envelope and life-cycle costs according to the present value method" (Weiche Einflussfaktoren der Gebäudehülle und Lebenszykluskosten nach Barwertmethode).

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