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Enabling Cumulative Improvement of Buildings-in-Use by Revealing Their Performance Gaps

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The thesis presents an innovative approach to development and proposal of solutions based on their value added to buildings. The approach is inspired by the ongoing DIGIBUILD project, which promotes the idea to reveal a performance gap by integrating and continuously comparing the actual and the intended performances of facilities. Such approach requires a shift towards a performance-focused business model. Consequently, value-based development of products and services enables cumulative improvement of a building ecosystem and enhances sustainability aspects.

The purpose of this thesis is to develop a roadmap of the performance gap revealing process, that is, to describe tasks, outcome, challenges and implementation practices. The study discusses such processes as performance monitoring and modeling, performance evaluation and benchmarking, as well as concerns critical drivers towards a performance-focused business model including procurement, value-based sales and performance-based contracting.

Generally, the study is conducted as an exploratory research, namely a design science approach. The literature and the analysis of three EU projects (PERFECTION, LinkedDesign, and TOPAs) contribute to the findings of research. While the literature facilitates the initial understanding on the performance gap-revealing problem, EU projects present the implementation cases and enable the evaluation against the DIGIBUILD concepts.

Keywords: Performance monitoring, performance modeling, performance evaluation, gap revealing, benchmarking, performance-focused business model, DIGIBUILD, PERFECTION, LinkedDesign, TOPAs

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Victoria Dudnikova

Content

Abbreviations and Acronyms

ASTM	American Society for Testing and Materials
BIM	Building Information Modeling
BMS	Building Management System
CAD	Computer Aided Design
CIB	International Council for Research and Innovation in Building and Construction
COBie	Construction Operations Building Information Exchange
DMPC	Distributed Model Predictive Control
EeB	Energy-efficient Building
EnPIs	Energy Performance Indicators
EPC	Energy Performance Contracting
EPG	Energy Performance Gap
ESCO	Energy Service Company
ESPC	Energy Service Provider Company
GDP	Gross Domestic Product
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information Communication Technology
IEC	Indoor Environmental Quality
IFC	Industry Foundation Classes
IoT	Internet of Things
IPMVP	the International Performance Measurement and Verification Protocol
IRCC	Interjurisdictional Regulatory Collaboration Committee
ISO	International Organization for Standardization
IT	Information Technology
KBE	Knowledge Exploitation Bundle
KPI	Key Performance Indicator

LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCE	Life Cycle Evaluation
PDA	Personal Digital Assistant
PLM	Product Lifecycle Management
POE	Post Occupancy Evaluation
QLM	Quantum Lifecycle Management
RFID	Radio Frequency Identification
ROI	Return on Investments
QIDMS	Quality Inspection and Defect Management System
WSN	Wireless Sensor Network

List of Figures

Chapter 1. Introduction

1.1. Research background and motivation

According to the Horizon 2020 Work Programme [28], buildings represent the largest source of energy demand and account for 40% of overall energy consumption. In addition, people spend most their lifetime inside buildings, making buildings quality and condition crucial for their well-being. This enhances the concern of the public for buildings sustainability. A sustainable building assumes attaining the required performance by deploying the minimum of resources, such as materials, finances, or workforce. Therefore, buildings' sustainability refers to improving environmental, economic and societal aspects. These three elements affect directly on the public prosperity and market economic competitiveness, thus producing the high interest from the governments of many countries. The public sector is an essential driver towards innovation and deployment of sustainable solutions. Therefore, the governments encourage this by developing performance-based regulations.

A performance-based approach is becoming increasingly popular in the modern society. Comparing with a traditional prescriptive approach, the performance-based approach gives actors more freedom in selecting means of design, engineering, construction and maintenance. As a result, product/service providers are motivated to develop and propose solutions that are more innovative and efficient. Furthermore, the performance-based approach reduces barriers in the international trade, which is highly important nowadays, in the circumstances of the increased globalization [19].

One of the essential aspects of the performance-focused development is creation and enhancing value for a customer. Hence, defining user needs and following performance requirements represent critical tasks. To assure value creation, the achieved performance should be verified benchmarking against the intended one. This requires continuous monitoring and controlling of the building condition. Performance indicators help to measure and express the building performance in a structured way. When information on the monitored performance is obtained, it can be compared with the potential performance, and the existing gaps can be identified. These performance gaps should lie on a base of developing new solutions, thus improving the buildings-in-use environment. Using such approach, customers attain deeper understanding on buildings potential and value added of the proposed solutions. Consequently, this amends the efficiency and productivity of building lifecycle value, and decreases operating and maintenance costs.

Today, various research associations and funds support projects and research initiatives devoted to improvement of the assets performance. Performance gap revealing refers to one of the approaches that enable cumulative enhance in performance quality. DIGIBUILD is a project, which inspires the gap revealing process investigated throughout this study. In addition, the thesis considers three related projects, namely PERFECTION, LinkedDesign, and TOPAs. The projects contribute to the DIGIBUILD research providing insights into the problem from different perspectives: data capturing, performance assessment, identification of performance gaps and automatic adjustment of models and parameters.

1.2. Objectives and research questions

This study investigates an innovative approach to developing performance-oriented products and services, which enables cumulative improvement of the building environment. The major interest lies on analyzing the process of performance gap revealing, that is, definition of enabling mechanisms and produced outcomes.

The objective of the thesis is to present a roadmap that describes the process of revealing a performance gap in details, as well as to provide insights into its benefits to building lifecycle value. Because performance gap revealing involves multiple steps, the study aims to define tasks required to perform. Each task is discussed further in terms of existing practices and methodologies, which are applied in the considering area. The final objective of the thesis is to investigate other EU projects that focus on the similar research problem. They constitute the implementation examples that contribute to the creation of the innovative approach to development and proposal of value-based solutions, providing critical information on successful and problematic aspects.

Therefore, based on the mentioned objectives, the thesis pursues the following research questions:

RQ 1. How and why revealing a gap between the potential and the actual performances will affect the overall improvement of lifecycle value of buildings-in use?

RQ 2. What tasks should be performed to reveal the building performance gap?

RQ 3. Where performance gap identification has been already implemented in practice?

RQ 4. What are key factors that make the process of revealing the performance gap challenging?

1.3. Structure of the thesis

The thesis consists of seven chapters. *Chapter 2* describes research methodology. It discusses the rationale and steps required to conduct a design science approach. *Chapter 3* introduces a performance-based approach and defines critical drivers toward buildings sustainability, that is, regulations and procurement. *Chapter 4* holds a deep discussion on tasks required to reveal the performance gap, as well as defines the context of a performance-focused business model. *Chapter 5* describes the proposed approach for performance gap revealing inspired by a DIGIBUILD project, and presents previous and existing EU projects, which investigate the similar problem. *Chapter 6* is a 'Discussion' part that relates to systematic answering the research questions by synthesizing results of the theory and the empirical part, as well as provides research limitations. Finally, *Chapter 7* presents conclusions.

Chapter 2. Research methodology

2.1. Design science approach

The investigated research problem is new and has specific practical significance. A research type that deals with ill-structured and particularly managerial problems refers to exploratory research. One of the methodological approaches, which conducts such kind of research, is design science. Design science aims to shape knowledge on a new phenomenon, thus improving the current practices [25].

2.2. Design proposition

Comparing with explanatory research, which assumes clear problem statement and reasonable theoretical background, exploratory research should define the initial problem and the understanding on it as a first step. This requires development of potential solution design.

Firstly, the current situation is described, and the existing problems that push the development of a new problem-solving approach are discussed in details. Thereupon, the intended situation is presented, which means defining why this supposes to produce the desired outcome and benefits to overcome the existing problems. Finally, actions and tasks required to move towards the intended situation are discussed.

A design proposition, or an artifact, represents a general frame that can be applied in designing a problem-solving solution. The artifact is formulated by means of realistic evaluation. This focuses on defining and evaluating systematically the intervention that is supposed to solve the problem in the specific context to achieve the desired outcome enabling the specific mechanisms [54].

2.3. Empirical testing

When a design proposition is formulated, it should be empirically tested. In the context of this study, empirical testing assumes comparison of the design proposition (i.e., the concepts of performance gap revealing process) with the similar propositions developed in several European research projects. This step facilitates understanding on what works and what does not work in the solution design. Empirical testing is a refinement phase, which evaluates and consequently improves the initial design proposition.

Chapter 3. Introduction to performance-based approach

3.1. Benefits of implementation

Today, sustainability is one of the major concerns of the governments around the world. Building sustainability assumes optimization of the building performance in all phases, such as design, construction and operation, in terms of minimization of deployed resources, reduction of environmental impact, and maximization of value added to the economy. Attaining such optimization goals is crucial for flourishing not only the building industry itself, but also for the societal prosperity in general. Buildings sustainability leads to significant improvement of buildings and environmental performance, as well as decreases operational costs.

However, application of the sustainable approach in building design and construction requires an interest from both customers (e.g., building owners or facility managers) and contractors (e.g., designers, engineers or constructors). Nowadays, customers do not often demand sustainable building solutions, because such solutions usually refer to employment of innovative technology or methodology. Thereby, these solutions are not widely experienced, and there is lack of information on their performance. As a result, this leads to a higher risk of occurring underestimated costs or incompliance with performance requirements [32]. Since customers do not trust or could be even not aware of the existing sustainable building solutions, contractors are not interested in developing and promoting them.

In order to stimulate demand for sustainable buildings, it is crucial to develop methods that define clearly sustainable building targets, assess the results of the proposed solutions, and express explicitly all their benefits to customers. Furthermore, all costs and risks associated with the proposed solutions should be accurately calculated, and these estimations should be presented to the customers to prove being reasonable and complying with a defined customer budget [32].

Another significant barrier to building sustainability is weak communication and networking. Maintaining a sustainable building requires close cooperation and information sharing among all relevant actors across design, construction and operation phases. For that reason, deployment of ICT tools is essential.

One of the tendencies for building sustainability is a performance-based approach. The performance-based approach represents a contrast to a traditional prescriptive approach, which assumes fixed use of materials and methods in building projects, strictly controlled by contracts.

In comparison, the performance-based approach focuses on setting not the means, but the results of a project [21]. This implies that a contract between a customer and a product or service provider defines the outcome performance of a building project. As such, customers can find an appropriate balance between cost and performance.

The performance-based approach stimulates innovation, which is an essential aspect of the sustainable building. Innovativeness can relate to processes, materials, or building components. However, in order to gain significant benefits, innovative solutions should focus on the overall improvement of the building performance, which means that enhancing one performance criterion while discouraging others is not acceptable [65]. To ensure that, it is critical to understand user requirements and targets, as well as to investigate other factors (e.g., environmental) that can restrict or affect the attainment of the desired performance goals. Since establishing user requirements is crucial, this leads to better understanding of a customer and as a result, higher satisfaction with a project. Furthermore, performance requirements should be adjusted to a type of a building (e.g., a residential building or an industrial building), because a purpose of its use and significance to the society or to a building owner affect the performance criteria and the performance level in general.

The performance-based approach requires establishing new ways of verification of the building project outcome. The verification aims to confirm that a proposed solution satisfies the defined performance criteria. The verification can be done inhouse or outsourced, and there are several methods to examine the results of the developed solution, namely tests, calculations, or a combination of both. Performance, that should be verified, includes technology-based performance criteria (i.e., facility performance is measured in terms of its physical parameters), and risk-oriented performance criteria (i.e., performance is evaluated against the reliability of the proposed solution to perform as expected) [19].

Overall, the performance-based approach brings significant benefits to customers and reasonable freedom to solution developers. A prerequisite for applying this approach is verification that all relevant actors have sufficient capacity, skills and motivation to innovate and satisfy the established performance criteria. However, the more performance-oriented building environment is, the more challenging is to define the universal level of the verified results.

3.2. Regulations

All buildings have to comply with a regulatory system of a specific country as well as to take into account international standards. Building regulations state goals and objectives that a building should comply with in order to meet the defined operational and functional requirements, performance criteria, and the overall societal needs. The regulations establish requirements and recommendations on such issues as a building structure, fire safety, heating, lighting, ventilation, plumbing, indoor air quality or energy, because all of them directly influence on safety, health and comfort of building users [48].

Although prescriptive (or, solution-based) regulation is easy to follow and verify their compliance, more governments are shifting their focus on developing a performance-based regulatory system. Performance-based codes define only the minimum performance level required to protect buildings' users from damages and hazards, but selection of means is a prerogative of contractors. Therefore, there are much less restrictions on materials and technology and more opportunities for innovation. However, it is still time-consuming and challenging to approve new technology by the government, which significantly reduces an interest of engineers to innovate [65].

Generally, the performance-based codes address such issues as sustainability, carbon footprint, noise pollution, durability, safety, security and affordability [16, 48]. Moreover, each country should adjust its codes to climatic and demographic specifics. For example, a current trend in most developed countries is the growth of ageing population, which raises the importance of regulating the buildings accessibility.

In order to be successfully implemented, the performance-based code should be complete, clear and understandable for all stakeholders, and it should avoid any multiple interpretations by different people. Furthermore, the performance-based code should present quantified description of performance requirements, taking into account the risk aspect [19].

The regulatory policies are developing on both national and international (e.g., ISO and ASTM standards) levels. There are also committees, which encourage international discussion on issues and challenges of the performance-based regulations. Examples of such committees are the International Council for Research and Innovation in Building and Construction (CIB) and the Interjurisdictional Regulatory Collaboration Committee (IRCC). Both committees support research and innovation in the building regulations. As for CIB, it has developed a set of requirements for performance-based codes (e.g., they should be easy to understand and apply; be flexible; assure certainty in outcome and compliance; encourage innovation). At the same time, IRCC develops documents to improve common understanding on the international regulations, as well as stimulates open environment for the inter-jurisdictional trade in design and construction [48].

3.3. Procurement

In the construction industry, procurement constitutes one of the most critical processes, which affects building sustainability as well as encourages or hinders innovation. Procurement can vary in different flows: depending on a contract type (that is, from price-focused to performance-based contracting); or based on risk allocation (i.e., all risks transferred to one party, or risks shared between a customer and a service/product seller) [75]. In addition, procurement can be performed in different procedures. Currently, a customer usually selects a service/product provider by means of the tendering procedure. Figure 3.1 describes steps of the procurement process.

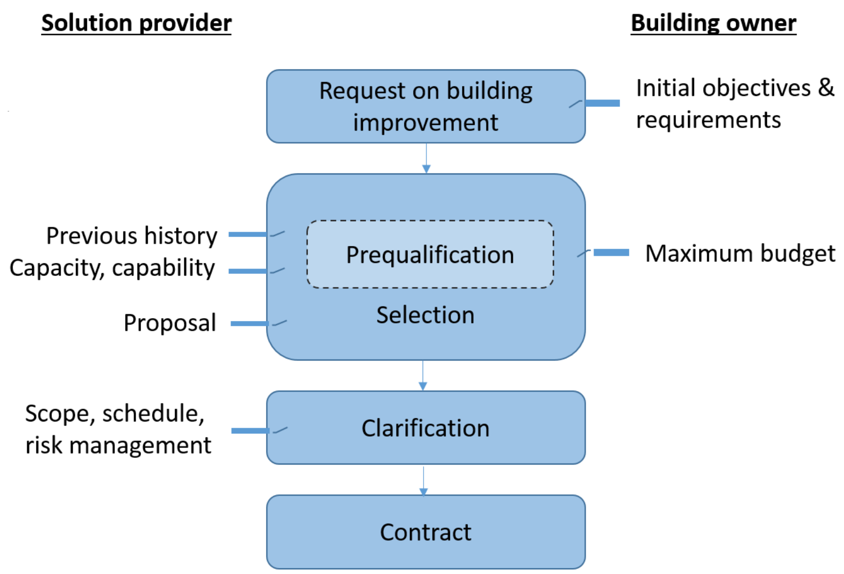

Figure 3.1. Procurement process

When a building owner realizes the need for some building improvement, it initiates the procurement process. First, the building owner or a facility operator formulates initial objectives and requirements of the upcoming project. Next step refers to selection of a service/product provider. The contractor selection can be performed as a single step (i.e., selection from all candidates) or as a two-phase process, namely prequalification and selection of the intended contractor. 'Prequalification-selection' variant is preferable, because it establishes the minimum requirement level.

In the prequalification step, the customer confirms that the potential contractor has sufficient capacity, technical capabilities, skills and financial resources to perform the defined assignment. The customer can verify contractor's reliability based on its past performance information. Furthermore, in this stage the contractor should gather details on a maximum available budget in order to enable development of the best-fit proposal in terms of quality and money. The intended output of the prequalification phase is a shortlist of contractors satisfying the established minimum project requirements. As a result, this reduces time wasted on further evaluation of inappropriate providers, decreases risks of the project failure, and generally improves the performance level of the further selection step. Moreover, it is recommended to conduct prequalification studies per project, to assure that selected contractors have sufficient capacity. However, such approach is resource consuming and thus rarely used in practice. For example, public clients apply a predefined list of contractors that are evaluated annually or even in the longer term [6, 75].

Thereupon, the potential contractors send their proposals to the customer. The customer conducts interviews and proposals weighting regarding risks, benefits and costs in order to identify the best proposal. When the intended contractor is eventually selected, it should clarify such issues as the scope of the project, its delivery schedule, and risks management. If all requirements are satisfied, the customer and the service/product supplier sign a contract [75].

Problems with the project outcome usually occur because of selection of an inappropriate contractor. This could be caused by setting improperly either selection criteria or methods, or their incorrect weighting. Generally, cost, time and quality form the main criteria in the selection process. However, other characteristics like contractor's qualification and project features are also critical.

Nowadays, the most important criterion for the contractor selection remains price, that is, sticking to the prescriptive approach. Consequently, quality of the building environment decreases, and risks of not complying with the defined project budget and time increase. However, an efficient and effective supply chain assumes minimization of any uncertainties and risks. For that reason, moving towards performance-based procurement is essential.

Performance-based procurement assumes making a trade-off between the price and the performance, which means that such critical issues as contractor's skills, experience and previous history of the projects performance should be taken into account. Furthermore, this approach aims to assure that both parties target at achieving mutual interests. This can be done by performance-based contracting, or sharing risks and responsibilities. Finally, the performance-based approach encourages reduction of control and management from a customer giving a solution provider more freedom [75].

Chapter 4. Towards cumulative improvement

4.1. Current problems

In addition to challenges defined in the previous chapter, like low demand for sustainable development and price as a main criterion for contractor selection, there are several other problems in the current building environment, which prevent buildings operating on their best level. Firstly, developed solutions do not often comply with the existing buildings. While the buildings are old, the proposed solutions are modern. As a result, the emerging innovative solutions are rarely implemented in practice.

Moreover, both service/product providers and building owners do not understand clearly where to deploy new solutions in order to produce the best value added to the buildings. This results in a situation, where service/product providers and designers do not know how and where to apply their development efforts to improve significantly the buildings performance. At the same time, building owners do not purchase the best available solutions on the market that can resolve specific problems of the buildings performance, which cumulatively exacerbates the buildings performance and the building ecosystem in general.

4.2. Revealing a performance gap

In order to understand which solution brings the best value added and to which building, there is need in revealing a building performance gap. The building performance gap refers to a comparison of the intended (that is, modeled) and the actual (that is, monitored) performances.

Today, performance modeling and simulation tools, as well as monitoring devices and methods attract significant attention in research and industry community. However, none of these processes (i.e., performance modeling and performance monitoring) itself cannot produce cumulative improvement of the building environment; instead, their interaction should be investigated. Dynamic revealing of the performance gap means continuous matching the modeling performance with the monitoring one in order to identify opportunities for improvement. The defined improvement opportunities are based on the current building problems, and leverage development of solutions that can overcome these performance problems. Therefore, this should improve the overall building industry prosperity, because solution providers develop and propose their products and service to such buildings, where the best value added exists. Furthermore, this promotes building sustainability in terms of reducing resource wasting and environmental impact in general, as well as improving return on investments of both a customer and a selection provider.

Modern information technology is an essential facilitator of the performance gap revealing process. IT is widely applied in industrial operations in order to simplify a decision-making process, as well as to optimize and improve various operation tasks. In addition, information technology often represents an enabling mechanism for innovation.

4.2.1. Performance monitoring

Performance of buildings can be monitored and controlled both manually and by means of modern ICT tools. One of the approaches to obtain information about the buildings performance is to conduct Post Occupancy Evaluation (POE) studies. POE studies aim to investigate building's serviceability (i.e., to ensure that a building satisfies the defined requirements that are essential to perform its functions) and to attain feedback from occupants. This is particularly crucial while implementing an innovative solution. Simple methods to perform POE include surveys, questionnaires and interviews. However, sometimes there is need to gain deeper understanding on the building durability, which requires to conduct more advanced methods, like site inspections or performance monitoring [7].

Performance monitoring and inspections can be assisted by mobile computing technology. Mobile computing enhances productivity and effectiveness of construction management, and stipulates avoidance of data duplication [37].

Examples related to mobile computing technology are PDA (or, Personal Digital Assistant) and QIDMS (or, Quality Inspection and Defect Management System). Such technologies help to collect data on assets (e.g., overall defect lists, defect frequency, quality inspection, or trades) and use this data further to manage actions required to correct and fix the identified defects. There are two reasons of defect occurrence: either final product does not execute required functionality, or the required functionality is improper, that is, it does not comply with the user's needs. QIDMS allows various participants of a project to access data in order to verify whether a final product satisfies the established by a customer safety and environmental requirements [36].

Generally, deployment of PDA and QIDMS provide important benefits for operation managers, such as faster retrieval of information and instructions, less error-prone information maintaining, easy monitoring of defects and corrective actions, an accurate analysis of defects' causes, and finally, better communication and information sharing among relevant actors [36, 37]. However, such technologies still require rather manual work (i.e., manual input of information into a tool), which is time-consuming. The solution could be an introduction of technology that enables automated data collection and processing. Therefore, a trend moves towards the Internet of Things.

The Internet of Things (IoT) is a global platform that enables machines and autonomous digital objects, which are designated as smart objects, to sense, compute, interpret and process data gathered from other smart objects or physical world, to react on it, and to communicate information to each other or to end-users. The Internet of Things has gained wide application in various industries, from infrastructure construction and logistics to public security and environmental protection [82].

Smart objects are key entities in IoT, which consume, process, and provide data. Therefore, they should be identifiable and able to communicate and interact with other physical and digital objects [64]. There are three types of smart objects [38], namely:

- Activity-aware objects (this is the simplest kind of smart objects that can only analyze and record data obtained from sensors without interaction with other objects);
- Policy-aware objects (smart objects that can process and react on events and activities according to the predefined organizational policies; endowed with the interactive capabilities);
- Process-aware objects (these smart objects are aware of the organizational processes, and can dialogue instructions about tasks, deadlines and decisions).

Because smart objects are heterogeneous, there is need in establishing a standardized communication protocol to enable their interoperability. Data fusion refers to a technique that simultaneously utilizes data collected from different smart objects [3]. Wireless sensors and RFID have attained a wide interest as means for identification and interaction of smart objects with the environment. However, RFID has limitations in use, that is, application only for objects identification and tracking [64].

A smart building is a new trend in the construction industry, which implements three main functions: automatic control, learning capabilities and occupancy trend incorporation [47]. Smart buildings enhance users control and safety, as well as support resource management, for example, by improving energy consumption. This raises a need for collecting various physical attributes (e.g., occupancy, indoor quality, external environment condition, or energy usage) by deploying specific sensors [80].

Since buildings are major electricity consumers, the problem of energy management is of significant concern. Acquiring data on power and energy use helps to predict power consumption and energy demand more accurately. A smart grid is currently applied technology in this field, and it represents an electrical grid, where all users are digitally connected to each other. Information exchange, supporting by the smart grid, affects positively perception, efficiency and sustainability of the overall electricity service [47]. Furthermore, the smart grid assumes performance monitoring in real time, which can be leveraged by WSN. There are three types of devices, which enable monitoring and interactive capabilities in WSN [81]:

- Sensors and actuators, which collect and further transmit data to a router, as well as perform instructions obtained from a communication node;
- A router that connects sensors and a gateway;
- A gateway, which task is to be an access point in WSN to other communication networks.

Generally, wireless sensor network is flexible and economic, but its considerable drawback is disability to transmit data in a long distance.

Because smart buildings facilitate enormous data collection from different smart objects, it causes a challenge to assure easy and efficient data storage and retrieval. Cloud computing can effectively resolve this issue. Cloud computing represents a flexible approach to manage IT resources by providing capability to share operating systems, applications, storage and processing capacity among users, and to regulate computing resources according to the demand for them [9].

The Internet of Things and smart buildings, in particular, enable automated control and actions triggered by indoor and external condition changes, which results in comfort and safety of building occupants, economic benefits (e.g., decrease in operational costs), as well as optimization of energy trade and reduction in environmental impact.

4.2.2. Performance modeling

Performance-based design assumes development, evaluation and selection of design options based on their compliance with performance criteria and functional requirements. While assessing performance-based design, a designer should analyze such critical building performance criteria as [76]:

- Comfort, which relates to different aspects of the indoor environment;
- Security, that is, design should prove safety of building users in an emergency, like fire or natural disasters;
- Economy, which means prediction of potential costs, operation and maintenance plans;
- Environment, that is, estimation of energy consumption, carbon footprint and emissions; and
- Structure that concerns, for example, residential planning and materials.

The performance-based approach requires presentation of performance criteria as quantified values. This is essential to enable comparison of different design alternatives. In order to analyze identified requirements and to model the overall performance of a design solution, designers deploy various analytical and simulation tools.

Such tools take into account various critical issues, like the building performance potentiality, environmental impact and compliance with national codes and international standards. Simulation tools assist in defining design solutions that enable the exceeding minimum performance requirements needed to comply with building codes, thus creating higher value for a building owner and occupants, and improving a competitive position of the designed solution on the market.

Generally, the focus of modeling tools lies on energy consumption, HVAC (Heating, Ventilation and Air Conditioning) analysis, natural and electrical performance, and acoustical performance [24]. Thus, they emphasize high quality, cost-efficient and accurate design and construction, and encourage sustainability of buildings. In addition, modeling and simulation tools perform an important lifecycle cost analysis of future asset operation. Using such tools, building stakeholders, thereby, obtain critical understanding on value, risks, serviceability, and optimal maintenance and lifecycle operation plans [32].

Furthermore, modeling and simulation tools can replace field tests, which are more expensive, challenging, and time-consuming. Since various test conditions (e.g., different climatic alterations) can be considered, this results in safer and more reliable design solutions [24]. In addition, energy consumption planners can benefit from using such tools by estimating and planning their energy trades more accurately.

Despite all mentioned benefits, simulation tools are still rarely used in practice. Most companies define simulation tools as expensive (that is, requiring higher costs and computational resources), time-consuming (i.e., most of the activities related to preparation for simulation and analysis of the results are performed manually) and demanding stronger competence and professional skills from the personnel [24]. As a result, most design decisions are made intuitively, leading to uncertainty and errors in design.

Another significant problem is a large amount of performance parameters that should be taken into account. One of the major challenges is to understand the interactions between these parameters as well as how each of them individually affects the overall building performance. Although these parameters could belong to different domains, their value is often interdependent. This means that, while making decisions in one domain, designers should consider attendant changes in other domains. Moreover, different performance parameters are evaluated by different evaluation techniques, that is, by different tools. The tools usually maintain own databases and the input/output interfaces. This makes performance tracking and conflict resolution across different domains extremely challenging, and leads to a problem of information exchange and data entry [7, 29].

However, if to refuse the deployment of simulation tools to perform preliminary studies on potential performance modeling, this can lead to further rework and increase in maintenance and operation costs. One of the approaches to resolve the defined above problems is to develop an integrated platform with a common database. This leads to decrease in time and costs required for decision-making, improves the consistency in assumptions made in each assessment domain, and as a result, improves design quality [29, 76]. It should also enhance communication capability and information exchange among all relevant actors, namely customers, designers and engineers.

Building Information Modeling is a tool that allows storing all information related to a building in one database, as well as representing and making this information visible and constantly available for all participants of a building project. Provided information includes both geometric representation (i.e., different technical and functional characteristics) and various engineering data obtained throughout a lifecycle of a building [40]. To assure interoperability and information exchange, there is need to establish standards for open data transfer. IFC and COBie represent examples of such standards. Currently, IFC has attained wider interest and application in the industry [33].

In addition, BIM supports automated generation and update of documentation, which enables all stakeholders possess the same and up-to-date information. Information can be presented in 3D CAD environment. Comparing with 2D presentation, 3D visualization enhances perception and understanding of geometric characteristics, relationships and needs among actors with different background [40].

BIM is used as a supportive tool in making decisions on financial affairs such as required investments and costs; providing information for lifecycle cost and environmental analyses; comparing alternatives and selecting one with the best value added and which is in agreement with sustainable building requirements [33]. For example, BIM is often deployed to simulate energy consumption. By integrating BIM and real-time monitoring, energy providers can investigate when, where, and in what amount energy is consumed in buildings, and thus predicting the energy demand more accurately [47].

Hence, Building Information Modeling brings benefits to each actor. Building owners support their property management processes and gain more accurate maintenance and repair schedules. Building users, at the same time, obtain quicker response to problems and requests, and as a result, this improves their satisfaction with the service provision. Service providers, including designers and engineers, can effectively collect, change, retrieve and exchange their business data [33].

BIM covers all phases of the building lifecycle – from design to operation. In a design phase, BIM enables modeling the facility management and the environmental impact (e.g., carbon dioxide emissions), automatic evaluation of design alternatives, identification and resolution of various design conflicts, accurate cost estimation and scheduling. In a construction phase, BIM is used to manage on-site activities providing their visualization and the opportunity to obtain all required information in real time. Therefore, BIM assures quality of a project, which results in less rework because of improved data sharing and communication, increase in project productivity, and improvement of overall satisfaction with the project. In an operation phase, Building Information Modeling facilitates more efficient and effective asset management, quicker response and higher asset value. Furthermore, it provides integrated lifecycle data to all relevant actors, which makes planning and management of operation and maintenance activities more precise and simple [40, 77].

Although BIM has multiple benefits that improve safety and efficiency during design, construction and operation of a building, some studies (e.g., [40]) state that not all industry actors are familiar with this concept, and as a result, BIM requires significant time and assistance for engineers and managers to deploy it. Moreover, some stakeholders disagree to share information with others, which constitutes one of the critical rationales for BIM usage.

4.2.3. Performance evaluation

Performance evaluation is a systematic, strategic-oriented task that assists companies in measuring various aspects of performance (i.e., evaluation from environmental, economic and societal perspectives), and in defining a performance gap between the actual and the desired service levels [2]. Performance gap identification is beneficial, because it gives essential insights into the development needs (that is, reveal which solutions are appropriate to the specific problem solving), and emphasizes a high performance level by minimizing risks of further demands for significant and costly reconstruction and refurbishment of an asset.

Recently, the industry has shown a considerable interest in environmental performance assessment, in terms of evaluation of energy consumption, indoor quality, emissions, and climatic changes. Examples of such-oriented evaluation tools are GPTool, BREEAM, or LEED. These tools present comprehensive frameworks for measurement of environmental performance issues, and verify the compliance with building sustainability targets [35].

Performance assessment is critical, because it enables efficient allocation of resources required on solving the proper operational tasks. This also improves condition of a building in a long prospect taking into account such critical aspects as health, safety and environmental issues. From the financial perspective, it supports investment justification, which is a crucial aspect for project customers [66].

There is a growing interest in monitoring and assessing the buildings performance by means of key performance indicators (KPI). KPIs help to understand condition of the building performance at the specific point of time and over some period, and can be used further as a basis in development of new alternatives for building improvement. Therefore, it is critical to identify explicitly a reference target for value of each performance indicator [4].

Traditionally, there are two types of performance indicators: key indicators (that is, indicators that are assessed periodically) and detailed indicators (that is, indicators that provide more detailed information on causes of the problem defined in a phase of periodical assessment). However, indicators can be further distinguished by their functional focus: equipment-related performance, cost-related performance, task-related performance, customer-related performance, environment-related performance, and learning- and growth-related performance [66].

Regardless of a type of a performance indicator, it should satisfy the following criteria: be objective, feasible, flexible, appropriate, cost-efficient, scientifically valid, and quantifiable; and enable easy use and data access in different phases of a building lifecycle, as well as support decision-making process [4, 35]. Although quantified (i.e., physically measured) indicators are preferable and commonly used, some KPIs cannot be presented by quantified value (e.g., social diversity, ecological value, climatic change, or usability) [31]. As a result, such aspects require the use of qualitative indicators, which are characterized as being unreliable and difficult to measure. A solution could be to present qualitative indicators in a grade system.

Generally, there is no limit in a number of indicators. However, it is crucial to consider performance indicators in total, that is, to understand interactions between the indicators and their implication on a building control system. Hence, a large number of KPIs is not preferable, because it influences negatively on the overall comprehension and the relative importance of each indicator [4].

The critical indicators that measure building sustainability for the whole lifecycle of an asset are LCC (Life Cycle Cost) and LCA (Life Cycle Assessment).

LCC is an economic indicator, which describes capital (or, initial) and in-use (or, consequential) costs, and assists in making a trade-off between them. LCC supports decision-making from the long-term prospect. This means that LCC analysis can help to prove the benefits of the option with higher initial, but less ongoing costs (for example, LCC leverages the employment of expensive, but more safe and efficient materials) [31]. Therefore, LCC optimization supports the principle of buildings sustainability and encourages innovation. LCC only focuses on the cost analysis regardless of the existing income streams. However, sometimes this is not enough to draw a valid comparison of solutions, therefore, LCC analysis can be extended to LCE (or, Life Cycle Evaluation), which accumulates lifecycle income data to LCC [55].

LCA is a method to assess environmental impact, and it can be presented as a four-step process [62]:

- Goals and scope definition;
- Inventory analysis (that is, definition of energy and other emissions along the building lifecycle);
- Impact analysis (assessment of the environmental impacts defined on the previous step);
- Improvement analysis (this step identifies improvement opportunities and proposes potential modification of analyzed products or processes).

LCA requires collection, store and analysis of a large amount of data during the assessment. Currently, there are different software packages that provide LCA service. These packages maintain advanced databases of environmental information and are used for product and process evaluation and improvement [62].

The considerable interest of this thesis is devoted to performance indicators that relate to assessment of indoor environmental quality. The indoor environment affects directly building occupants' well-being, and thus related KPIs focus primarily on assessment of health and comfort aspects. Such KPIs are generally divided into five core groups: indoor air quality, thermal comfort, visual comfort, acoustic comfort, and quality of drinking water [68].

The goal of KPIs devoted to indoor air quality is to control and minimize a level of pollutants by monitoring indoor air quality, identifying potential problems and their causes [31, 68].

As for thermal comfort, main performance indicators are air temperature, mean radiant temperature, air velocity and humidity. These indicators are critical because they directly influence on biological and psychological well-being of building users as well as monitor energy use and carbon dioxide emissions [31].

Key performance indicators measuring visual comfort include illuminance and daylight factor. The KPIs check whether the current lighting solution produces sufficient light to perform required visual tasks, and to assure safety in a space. It is crucial to support a high level of visual comfort, since it affects comfort and efficiency of energy resource consumption [31, 68].

The objective of acoustic comfort KPIs is to reveal that acoustic performance is sufficient to conduct required acoustic tasks.

Finally, quality of drinking water is monitored by KPI to prevent and control legionella in the building-in-use water system [68].

4.2.4. Benchmarking

Benchmarking is a strategic tool that enables continuous performance improvement by assessing and comparing the potential and the intended performances, and exploring the opportunities for building improvement. Hence, benchmarking represents a tool for performance measurement and management [78]. It supports development and cumulative improvement of competences of an organization and as a result, produces better service to customers. The cumulative improvement of performance leads to cost and quality optimization.

Generally, benchmarking enables improvement of a product or a process by comparing the current one with the best available option. For example, solution providers can benchmark their products/services against other solutions available on the market, and develop such solutions that are both relevant to the building specific problems and complying with the best practices in the industry. Therefore, benchmarking continuously aims to investigate and implement best practices and innovative ideas, which supports achievement of superior performance [2, 5].

The literature defines several types of benchmarking depending on its goals and process [5]:

- Performance benchmarking – a company compares various performance metrics, like reliability or quality;
- Process benchmarking – focus on improvement of routine operations;
- Strategic benchmarking – search for best strategies that are expected to be successfully implemented in the benchmarking company;
- Competitive benchmarking – comparison of performance, a product or service with the competitor’s one. This is the most challenging approach, because naturally no one wants to share information that can represent a competitive advantage;
- Cooperative benchmarking – applying experience shared by the benchmarked company which is not a direct competitor;
- Collaborative benchmarking – represents a collaborative initiative in improving companies’ performance, products or service, and can be presented as a brainstorming session;
- Internal benchmarking – investigation of best practices and improvement opportunities within the company, which requires comprehensive understanding on the company performance as a whole.

Applying benchmarking technique should considerably encourage innovation and improve the societal prosperity and flourishment. Furthermore, benchmarking is to decrease costs and increase profits of both a solution provider and a building owner, because of the optimization of processes and proposed solutions. In addition, benchmarking promotes excellence in operation and maintenance, as well as provides deep understanding on resources required to achieve superior performance.

In order to attain all benefits from benchmarking, companies should ensure that the results of benchmarking agree with the corporate strategy and vision [78]. Moreover, a purpose of benchmarking should be defined and explicitly expressed.

Benchmarking needs evaluation mechanisms and information to prove the advantages of the proposed solutions [5]. Communication should be extensive and transparent from the beginning to enable data acquisition [78]. Concerning external benchmarking, performance indicators should be transformed into a standardized form to assure the validity of their comparison with indicators of other companies [2].

Finally, benchmarking has received the growing interest in assessment of building sustainability. However, in the building environment a comparison of performance criteria has some specifics. Performance criteria to a large degree depend on local context, a building type, a pattern of usage, or expected service life; therefore, it is crucial to assure a functional equivalence regarding a purpose of benchmarking. The functional equivalence assumes achievement of minimum requirements in technical and functional characteristics of the building [31].

4.3. Changing a business model

Revealing a performance gap requires movement towards development of a performance-focused business model, which concerns performance-oriented contracting and value-based sales. Currently, the building industry is characterized as being project-oriented, where different actors participate in many different projects throughout a lifecycle of a building. As a result, neither building owners, nor solution providers (including designers, architects, manufacturers, service or product suppliers and other contractors) aspire to share information on the project performance and invest in solutions that produce the most significant value added to the overall building performance. Thus, there is need for switching the roles of a solution provider and a customer. In this new approach, a building owner represents a supplier of the relevant information on the actual building performance. In contrast, a solution provider tracks this information to make a decision on a building performance gap. When the building performance problems are public, the solution provider can focus its efforts and resources on developing solutions that can close the specific performance gap. Therefore, since both sides (i.e., a building owner and a solution provider) obtain up-to-date information on the performance, they can make better investments into building design, construction and operation activities.

4.3.1. Performance-oriented contracting

There are three typical forms of contracts, namely fixed price, fixed unit price, and variable budget. A fixed price contract is the most widespread contract type, which best comply with the tendering procedure. Since the major criterion for supplier selection in a tender is often the lowest bid, contractors aim to create their proposals on the lowest possible price. As a result, a contractor is not motivated to perform risk analysis, because this increases its proposal price. Thus, fixed price contracts are highly uncertain in terms of possible risks concerning time and budget overrun. However, because the price is strictly defined in a contract, risk and responsibility for any additional expenses belong to a contractor. This gives some safeguard for a customer. At the same time, if a contractor is able to perform a project with less cost, it can make a margin. Generally, a customer and a contractor have different goals and interest, which hinders superior quality of the project performance [13].

The concept of fixed unit price is similar to the fixed price contract, although a contract defines not the overall project price, but only price for a delivered unit. The unit constitutes a small and repeatable unit. This means that the more units are delivered, the more a customer pays. Despite dealing with the risk of cost overrun, there is not mutual goals of both parties. Therefore, in order to increase a margin, contractors can overcharge unit prices in their contracts [13].

Comparing with the previous contract types, variable budget does not define fixed costs and prices in a contract. This encourages customers to select contractors based on quality of their proposals. The payments are only made for hours worked in a project. Although there are some benefits for both a contractor and a customer, this type of contracting is highly unpredictable, and thereby rarely used in practice [13].

Performance-based contracting (or, outcome-based contracting) is a relatively new type of contracting mechanism, where customers pay for the delivered outcome [50]. In order to achieve the desired outcome, a customer should firstly define its needs in terms of performance requirements. Then, contractors implement these requirements in their technical solutions. To prove that solutions actually produce the intended outcome, it is essential to measure performance requirements. This means that related methods and data should be available [22].

Performance-based contracting leverages risks sharing between a contractor and a customer. It also enhances achievement of mutual interests of both sides, because a solution provider cannot deliver any outcome without value co-creation with a customer. Generally, benefits from this type of contracting include considerable reduction in costs and financial audits; improvement of customer needs understanding; and as a result, increase in customer satisfaction.

Performance-based contracting is widely applied in the public sector, for example, in transport, health care, or the defense industry. One of the examples of performance-based contracting is performance-based logistics. Its rationale is that a contract focuses on the performance outcome, rather than defines tasks and inputs from a service provider [50].

4.3.2. Value-based sales

Value-based sales focus on identifying customer needs and response to these needs by developing the best value added and durable solutions. The peculiarity of such type of sales is a shift from considering the explicit needs to investigating the latent ones. This makes value-based sales more challenging comparing with a traditional selling approach, and requires close cooperation between a solution provider and a customer [70]. Such cooperation relates to a process of value co-creation. Value co-creation assumes joint contribution of resources from a solution provider and a customer to problem solving. Examples of such resources could be knowledge, expertise, or budget.

In the process of value co-creation, the aim of solution providers is to develop and offer a value proposition, which means that they do not produce any value themselves; at the same time, customers are responsible for defining value and co-creating it with the provider [50]. However, in order to co-create value successfully, both parties need to understand objectives and outcome of the solution development [1]. Furthermore, it is crucial to assure that a solution provider has sufficient competence to avoid futile time, money and other resource wasting.

The process of value co-creation can be roughly divided into three steps: understanding the customer's needs and business specifics; development of a value proposition; and communicating the value to the customer [70].

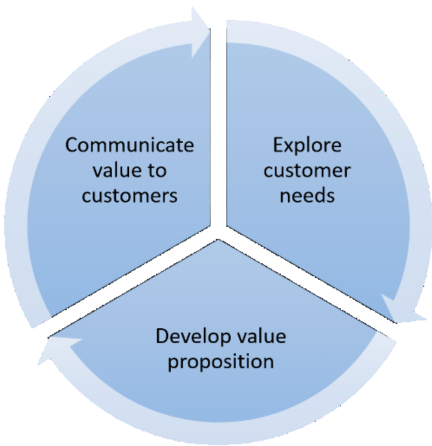

Figure 4.1. Value co-creation process

First, a solution provider identifies explicit and implicit needs and analyze a customer's business model. When a deep study is conducted, a customer and a seller negotiate it, specifying the problem in context in details. Thereupon, a solution provider develops value propositions, and discusses their potentials and required resources with the customer. This requires application of various quantification methods, such as value calculation, simulations, ROI (Return on Investments) definition, or lifecycle costs calculation [70]. These methods reveal the quantified benefits of the proposed solutions to the customer's business, which makes assumptions more trustworthy. The result of this stage is selection of the optimal value proposition. After the value proposition is determined, value can be co-created with the customer.

A critical role in value-based sales is given to communication between a customer and a solution provider. To provide a value proposition, producing significant benefits to a customer, the latter should announce its recommendations on budget, schedule, and provide information on the predicted use, business context and needs. However, the major problem is that customers often do not realize their actual needs, which makes a dialogue more challenging and requires a solution provider to be more proactive [1].

It is also essential to assure mutuality of goals and interests between both actors. Furthermore, value-based sales assumes shifting risks and responsibilities of some customer's processes and activities to a solution provider [70].

Although value-based sales have many advantages that result in long-term survival and growth [70], this also enhances interdependence between customers and providers. Solution providers require advanced information from customers to develop a beneficial value proposition, but customers do not always have sufficient ability or desire to provide it [1].

Chapter 5. Industry best practices

5.1. DIGIBUILD project

DIGIBUILD is a new project, started in March 2016, which promotes the idea of development sustainable solutions that close specific performance gaps, and thereby, cumulatively improve a buildings-in-use ecosystem. DIGIBUILD encourages a shift towards a performance-focused business model, which requires changes in the current practice of product/services development and solution provider selection.

The project proposes to enhance buildings lifecycle value by developing and selling solutions that bring to customers the best value added, which means rational allocation of developing efforts and investments. The DIGIBUILD approach implies the idea of making a building performance gap public, thus giving opportunities to solution providers to design and propose solutions that can resolve a certain performance problem.

Making performance gap visible assumes integration of the monitored and the modeled information. This means that both kinds of information should be available and public, in order to leverage designers and engineers to develop solutions based on the customers' existing and particularly latent needs. Furthermore, integration of related information and automated exploration of improvement opportunities require the development of interactive information systems and decision support tools. Figure 5.1 presents a framework of the DIGIBUILD proposal. It defines the context and tasks required to enable value-based development.

Overall, an approach proposition can be presented as following: *Moving towards a performance-focused business model, reveal a performance gap by means of integrating and comparing monitoring, modeling and simulation information, and switching the roles of a solution provider and a building owner in order to cumulatively improve lifecycle value of buildings-in-use*.

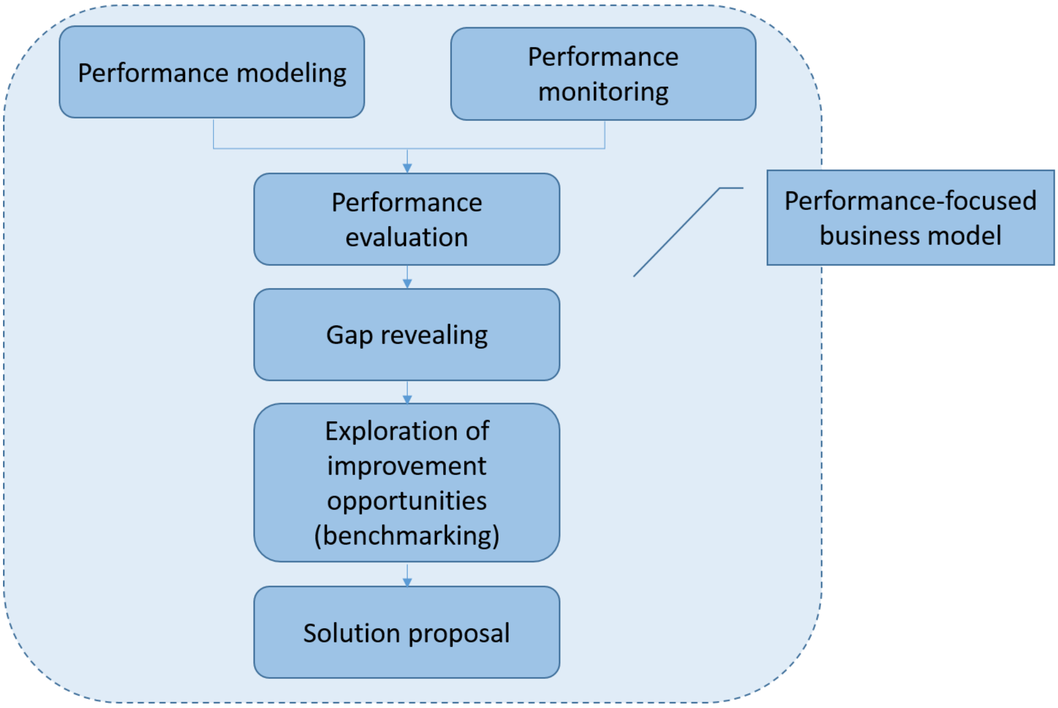

Figure 5.1. Tasks enabling value-based development

5.2. PERFECTION project

5.2.1. Project objectives and value

Recently, European Union has initiated several projects, which encourage research on building sustainability. Indoor environmental quality (IEQ) represents a critical issue that affects significantly building sustainability. The indoor environment indicates how people feel themselves inside buildings. Because people tend to spend the most part of their life inside the buildings, maintaining a high level of building indoor performance is crucial. It affects physical and mental health, as well as comfort of building users. One of the research initiatives designated to improve building indoor quality is a three-year PERFECTION project, which was launched in January 2009.

PERFERCTION project aims to achieve several objectives. The first objective is to create a performance assessment framework. The framework summarizes a complete set of key indoor performance indicators that are relevant to assessing, designing and renovating the indoor environment of each specific building type.

The project focuses on five building types: residential buildings, offices, schools, hospitals and exhibition buildings. Each building type has its specific requirements for indoor quality, thus making critical to adjust significance of performance indicators to the assessment target.

The performance assessment framework represents a tool, which helps to reveal the overall performance of a building evaluated in a structured way [57]. Furthermore, the tool should enable utilization of the proposed assessment methods at the European unified level. This enhances buildings benchmarking against a standard performance level.

After developing the performance assessment tool, the second objective of PERFECTION is to implement this theoretical framework in practice. To ensure reliability of the tool, it was firstly tested in ten case studies. Thereupon, the PERFECTION team has developed an ICT toolbox, which represents a web-based platform, where all interested actors can communicate to each other. The platform tasks include evaluation of products, services and facilities against the KIPI model, publication of the assessment results, and search of best practices and opportunities for improvement. The toolbox aims to reinforce information exchange and data sharing on up-to-date buildings' conditions, as well as to promote innovative products and services that significantly contribute to IEQ.

The PERFECTION project encourages building sustainability by revealing direct and indirect benefits of sustainable design and development, for instance, economic incentives or easiness of understanding and application of new technology [39]. The assessment tool leverages evaluation of the proposed solutions in terms of their economic, environmental and social impact. From a long-term perspective, the project aims to enhance innovation and encourage application of new design and technologies in the building industry [56].

The project targets three user groups including building industry stakeholders (e.g., designers, product or service providers), building users (that is, owners and building tenants) and policy makers that are responsible for developing regulations and standards. The PERFECTION project set value for all three user groups. Building owners can understand problems and areas for improvement based on the results of assessment of their facility performance. They can further search for solutions available on the market, which provide the best value added to their specific building. Solution developers can benchmark their products and services against other proposals, as well as easily search and communicate with potential customers who would gain the best benefits from their proposals. Finally, policy makers can access to the best industry practices and stimulate their application on the market by developing and improving local polices and standards [20].

Overall, the innovativeness of the PERFECTION approach lies on developing a framework that brings together all relevant indicators, and proposing a unified method for evaluation of buildings performance [39].

5.2.2. Proposed solution

As a starting point of development of the performance assessment framework, that is called PERFECTION KIPI, a project team investigated the existing standards, regulations, policies, new and emerging technologies, and research activities, which consider the problem of the indoor environment of buildings. Overall, building regulations of 27 countries have been analyzed. As being an EU-funded project, PERFECTION focused on European regulations, considering the following four documents as the core ones: the Energy Performance of Building Directive, the Construction Products Directive, the European Environment & Health Action Plan, and the Green Public Procurement Policy [15]. The result at this point was producing a list of more than 100 indicators. However, the initial set of indicators was too long to satisfy the intention of the project to create a practical and simple performance assessment framework. Therefore, the list of indicators has been further shorten after consulting with experts in the building industry. The consultancy included primarily online questionnaires, but also interviews with the related stakeholders [57]. Eventually, 31 indicators form the final KIPI assessment framework (Appendix A).

KIPI has a hierarchical structure that consists of three levels. The first level (i.e., an abstract level) represents of a list of core indicators. There are four core categories of indicators: Health and Comfort; Safety and Security; Usability and Positive Stimulation; and Adaptability and Serviceability. The second level contains eight performance indicators, which describe core indicators. Finally, the third level forms a list of 31 technical indicators and parameters [30]. These indicators represent quantitative, qualitative or descriptive parameters that can be further assessed.

In order to simplify understanding of the framework, each indicator is supplied with the following details [67]:

- Name, which enables easy identification of the proper indicator among the whole list;
- Description, which presents a short description of the indicator's meaning;
- Unit, that is, an indicator's unit of measure; and
- Assessment method. There are different methods of performance evaluation depending on a current stage of a building lifecycle.

Generally, the project is devoted to assessment of buildings in either design, or operation phases. However, in both cases indicators are evaluated by a five-level performance scale, namely by one of the letter in a range from A to E. The letter 'A' refers to the highest performance level of an indicator, and 'E' to the lowest level, respectively. Class 'D' states the minimum regulatory performance level [58].

Although there are 31 indicators in total, it is not mandatory to assess all of them. The reason is that different buildings have different requirements to indoor quality depending on their function, and as a result, some indicators could be irrelevant to the specified building type. Moreover, indicators have various importance to the building, which should be taken into account in building assessment. Assigning weights to the indicators can resolve this issue.

The weighting of KIPI is based on a theory of Multi-Criteria Decision Analysis. This approach enhances development of subjective judgements and decision-making in a structured way. Each indicator gains the weight in a range of 0-1, which reveals its subjective importance in the overall performance assessment and can reflect local regulatory specifics (Appendix B). The total value of all indicators' weights should be equal to '1'. Furthermore, the weighting represents a bottom-up procedure. This means that weights are firstly assigned to technical indicators (level 3), then to performance indicators (level 2), and finally to the core indicators (level 1) [30]. In the KIPI environment, a user has a choice either to apply the proposed weights, or to set his/her values according to own agenda and priorities. However, if different users evaluate similar buildings using their personalized weights, this makes the reliable comparison of such buildings impossible. Thereby, this discourages benchmarking opportunity, which forms the critical value in the PERFECTION project.

In addition, KIPI defines the impact on building sustainability (i.e., social, environmental and economic aspects), which each indicator produces. The evaluation is performed by means of a three-level scale. The highest impact is designated as '3 stars' symbol, while one star represents the lowest impact, respectively. The white star denotes irrelevance of the indicator. Overall, the weights and the impact on sustainability reveal significance and priority of the indicators to each considered building type [67].

Further, the KIPI framework is implemented as a web-based platform, where users (both building owners and solution providers) can assess their assets. The online indicator toolbox consists of two sections. The first section collects general information on a building, including its location (for example, country and address), project participants (including an owner and an architect), a building type, a lifecycle stage, site information (e.g., a gross-floor area), and a number of occupants [67].

The second section concerns evaluation of performance indicators. When the weights are assigned and the indicators are assessed, KIPI calculates a score of indoor environmental quality, that is, a number in a range of 0-100 (Figure 5.2 presents an example of a KIPI score). The score can relate to the overall building performance or define separate value for each core indicator. Since some indicators can be irrelevant or present low significance for building assessment, they are not taken into account in score definition. Moreover, there is no penalty for excluding any indicators from the calculation. However, this affects the reliability of the assessment, which is reflected by the KIPI coverage. The KIPI coverage illustrates a percentage of indicators used in assessment to their total number. The developed toolbox publishes this information in the platform [58, 67].

Indoor environment quality	
Total KIPI score	**67/100**
Health and Comfort	52/100
Safety and Security	93/100
Usability and Positive Stimulation	62/100
Adaptability and Serviceability	69/100

Figure 5.2. KIPI score (Source: http://cic.vtt.fi/kipi/showcase.php?project_id=153)

In addition to the assessment functionality, the web-based platform performs as the information exchange and communication channel between building owners and product/service sellers. For example, user forum enables fast and easy attainment of additional information.

Overall, the PERFECTION web service for evaluating the indoor performance quality presents the following main features [20]:

- Solution providers can publish information on their products and services that have been preliminary evaluated against the KIPI framework;
- Building owners can publish information on their facilities assessed by KIPI indicators;
- Both parties can obtain email notifications when there are any uploads related to the interesting performance indicator;

- Solution providers as well as building owners can freely browse across all services searching the best value added offerings and investigating indoor performance benchmarks;
- All stakeholders can directly contact the required actors through the platform.

5.2.3. Evaluation against the DIGIBUILD approach

The major interest of the PERFECTION project is to propose the assessment of buildings performance in a unified way. This can be done by developing a simple and standardized performance assessment framework, and by providing online services to make performance assessment information public. The project stimulates the development of solutions in circumstances of applying a performance-based approach and moving towards value-based sales. Assessing building condition and revealing performance gaps should encourage innovation and knowledge-focused development, thus improving the overall quality of the indoor environment.

Generally, PERFECTION and DIGIBUILD projects have many similarities in their approaches, which allows comparing the projects gradually using the concepts of the DIGIBUILD framework.

Performance modeling & Performance monitoring

In the PERFECTION project, discussion on performance modeling and monitoring mainly concerns the application of key performance indicators. The project states that KPIs are necessity, which enables designers to identify critical points in design. Thereby, KPIs help to state performance objectives, assess and monitor the current condition and performance progress of facilities [30].

PERFECTION proposes the following process of collecting information on building performance. First, simple performance assessment methods should be applied. This includes expert reviews and surveys (e.g., POE). However, if an indicator is critical for a specified building type, advanced assessment methods can provide information in details. The advanced assessment methods include different simulations and measurement. Furthermore, it is highlighted that design and operational phases support different approaches to collection of information on building performance. While in a design phase assessment can be performed only by expert reviews or simulation tools, in an operation phase on-site activities are also capable of being conducted [57].

Overall, the project holds only shallow discussion on performance monitoring and modeling. Moreover, there is not detailed research on modern tools and technologies that can be deployed for these tasks (e.g., BIM or IoT).

Performance evaluation

Performance evaluation is a core objective of the PERFECTION project. The project focuses on development of the performance assessment framework, KIPI, which has the potential to become an EU standard [39]. The main concepts and principles of performance assessment are presented in the 'Proposed solution' section.

Generally, PERFECTION concerns performance evaluation in two separate phases – building design and operation. The goal of performance assessment on a design stage is to verify that the predicted performance of new buildings or buildings under renovation satisfies the required performance level. From the other side, performance evaluation in an operation phase aims to measure current performance condition of existing facilities and define possible actions to improve it [67].

Furthermore, because buildings are often employed for several functions (i.e., different activities could be done inside a building), this results in a variety of performance requirements. Therefore, the project recommends evaluating building indoor performance separately for each activity area [57]. This enhances understanding on the actual building performance, and enables accurate definition of required corrective actions.

Finally, evaluation is conducted under a performance-based approach. This assumes analysis of performance indicators as a basis for performance judgements, while indirect assessments by means of prescriptive requirements and assumptions on technological solutions are not applicable [58].

Benchmarking

Benchmarking represents an essential process in the PERFECTION project. The tool developed under this research allows citizens and particularly construction experts to benchmark buildings against a standard performance level. There are five building types considered in the project. In order to assure reliable benchmarking, each building type should refer to its own standard performance level. A building that achieves the standard performance level relates to a reference building. The reference building assumes that performance of any indicator related to this building type is satisfactory and complying with EU standards and regulations. Although there could be some differences in regulations across Europe, the project recommends standardizing the reference buildings in order to enable the building comparison between countries [67].

The PERFECTION does not support the complete benchmarking process, but focuses on maintaining a database of building cases, which enables users to access to best practices available on the market [39].

Gap revealing

Making performance visible is one of the crucial goals, which the developed web-based service should perform. The tool enables definition of both the actual and the potential performances. However, in the PERFECTION project the process of performance revealing is static, which means grading the building performance by a letter. KIPI score presents a total gap between the intended and the actual performances. All performance assessments must be executed by means of the KIPI framework, which constitutes a unified method for presenting the building indoor performance.

Exploring improvement opportunities & Solution proposal

A benefit of the proposed approach is that solution providers can search for opportunities in closing a performance gap, while verifying the current condition of the assessed buildings. Solution providers can specify from one to three indicators that their solutions focus on. Using this information, the providers can browse or request such assets, where specified indicators have low performance. Thereby, they can further propose their solutions to customers, who would attain the best value and thus would be potentially interested in these solutions.

Such approach results in more reasonable and knowledge-based development and promotion of solutions that significantly contribute to indoor environmental quality [39].

Performance-focused business model

The PERFECTION project aims to change the current business model by encouraging value-based sales. This enforces the development of solutions based on information about market demand, and stimulates the innovation initiatives in the industry. The PERFECTION project also concerns a risk management issue considering information exchange as an essential way of risks minimization [20]. Building users are involved into product/service creation from an early stage, which leads to better understanding on their needs, optimization of investments and resource usage, as well as higher customer satisfaction with the proposed solutions.

5.3. LinkedDesign project

5.3.1. Project objectives and value

LinkedDesign is a European Union project, which aims to improve current practices in design and manufacturing phases. Manufacturing has critical value for the European economy, since it makes a significant contribution to GDP and market workforce. Improving productivity of this sector is essential for the European economy growth and competitiveness on the global market. Therefore, EU has launched new research initiative that should stimulate flourishment of the manufacturing sector [41].

The main output of research is development of the integrated information system. The information system focuses on providing user-centric lifecycle information management, and performs the following tasks, which initially constitute the objectives of research [41]:

1. Collecting all information concerning a product regardless its format, location and a phase of a product lifecycle;
2. Providing analysis and context-driven access to product data, which means the system enables sorting and displaying data to users according to their roles and assignments;
3. Enforcing users collaboration (i.e., the system provides advanced social networking capabilities, which help to search appropriate competence and know-how solutions fast and easy inside the company);
4. Transmitting feedback into the existing system.

A manufacturing product lifecycle is rather long and consists of five phases, which Figure 5.3 presents.

Figure 5.3. Phases of manufacturing machinery and equipment lifecycle (Source: [63])

Generally, each phase generates some sort of product data, which can be used on further lifecycle stages. Hence, an enormous amount of data occurs along the whole product lifecycle, which is usually spread across various data sources. Currently, employees often search required information on products manually, wasting a significant amount of their worktime and making a process of data collection time-consuming and error-prone. LinkedDesign aims to resolve this problem providing a flexible and low-maintenance solution that enables easy search and federation of data related to product design or production [79].

Moreover, data is often stored in different formats including both structured and unstructured. One of the project goals is to enable data integration, which ensures capturing all relevant data (e.g., text, pictures, illustrations, technical specifications), but eliminating unnecessary data duplication.

In addition to data integration, it is crucial to ensure that all project participators have access to the required data. The participators have different roles in a project and have different demand for information. Hence, there is need to support context-driven acquisition of information. Furthermore, conducting assignments, employees often collaborate with other project stakeholders, thus enhancing the criticality of information exchange and sharing across multiple departments or even different companies. Supporting context-driven data management encourages exchange of information among relevant actors and simplifies a problem-solving process making easier to search people responsible for the assigned tasks.

Generally, LinkedDesign aims to improve design efficiency and sustainability, and to provide services for fast assessment of design alternatives (e.g., LCC/LCA analysis). As for manufacturing, the project improves quality management by means of providing services to monitor data obtained from a site and comparing this data with the initial design.

Hence, the developed integrated information system presents a single entry point for displaying all lifecycle data concerning each specific product. This leads to easy retrieval of required information, thus significantly decreasing time spent on information search and improving information representation because of reduced duplication of similar information. Furthermore, the proposed approach helps to avoid employment of external tools for performing analysis on retrieved data and visualizing the data in proper reports and presentations [43]. Finally, the system encourages remote and real-time communication between actors and departments within and across the organizations. As a result, this simplifies sharing of ideas and concepts, increases quality of service provision, and decreases time required to resolve the occurred problems and to release a manufacturing product on the market.

5.3.2. Proposed solution

During the project a web-oriented integrated information system has been developed, which is called LEAP (or, Linked Engineering and mAnufacturing Platform). Leap represents both a search engine, which explores knowledge as well as captures, updates and shares up-to-date information across departments and organizations, and a decision support tool that can be used for further data analysis.

Leap focuses on three major user groups, such as designers, engineers and production operators, but also targets other stakeholders that can contribute to product manufacturing, like service providers, suppliers or marketing experts [43]. For example, using the Leap platform, designers can perform comprehensive analysis considering advanced parameters, which results in developing more value added and competitive solutions. On the other hand, during an operation phase, facility operators can acquire data from a site to monitor quality of the production process.

Main usage tasks that Leap is expected to perform (i.e., capturing an enormous amount of data and knowledge, real-time information sharing, or reports generation) stimulate the deployment of cost-effective and widely accessible technology, as well as support the remote and distributed work [43]. Therefore, Leap operates in a cloud platform.

Leap is a dynamic platform, which assumes gradual buildup of functionalities over time [43]. Therefore, Leap pursues a service-oriented architecture. The platform architecture consists of three layers: the User Interfaces Layer, the Service Layer, and the Data Sources Layer.

The highest layer, namely the User Interfaces Layer, presents UI components that enable user interaction with the platform, that is, data collection and analysis, reporting, and communication features. This includes the following user interfaces [53]:

- Chart-based reporting;
- MS Excel Plug-In;
- KBE Integration GUI;
- MS OneNote/Word Plug-In;
- Graph Visualization;
- Matching UI;
- Production Line Realtime Monitor;
- 3D CAD Browser;
- PLM Statistics;
- Lifecycle Data Analysis;
- Virtual Obeya.

Virtual Obeya is a front-end of the platform, which represents a single entry point to the Leap functionality. In Virtual Obeya information gathered from the previous layers is integrated and shared to users' desks and workspaces. In addition, Leap supports collaborative environment from SAP StreamWork. StreamWork is a decision-making platform that aims to provide collaboration services, improve team productivity, and support synchronization services through real-time information sharing and notifying on the latest uploads and activity changes [41, 43].

The Service Layer defines a set of services that Leap is supposed to perform, thus forming the platform functionality. Generally, services can be divided into two groups: data services (i.e., services that support data filtering and retrieval from data sources), and Leap services (that is, services with the predefined UI, which enable the specific platform functionality). Standardized communication interfaces (e.g., QLM MI) are required to interact and gain access to services. The following services organize the middle layer of the Leap architecture [53]:

- Chart-based Reporting Service – enables creation and edition of reports;
- Knowledge Acquisition and Codification;
- KBE Service – is a framework that enables users to identify the best

problem-solving option by capturing and reusing product and process engineering knowledge;

- Object Matching Service – applies for data integration from several sources by identifying semantic relevance between objects and preventing data duplication;
- Smart Links Infrastructure – supports automatic computing of links between data objects;
- Schema Matching Service – automatically calculates similarities between elements of two data structures;
- Semantic Mediator Service – responsible for data integration and provision to project-related actors;
- Semantic Reasoner Service – enables rules management, which increases time efficiency and supports quality assurance;
- Measuring Data Processing and Sensor Data Analysis;
- Dialog – a middleware that receives data from real-time monitoring tools (e.g., machine sensors) and transmits this data to PLM Data Service;
- PLM Data Service – establishes matching between data collected from sensors or measures and physical objects, as well as provides an object's history along the whole product lifecycle;
- Instance Importer – creates an instance of the ontology and imports data in the required storage mechanism; and
- LCC/LCA Analysis.

The Leap platform provides an opportunity to conduct analysis and define the best alternative that satisfies needs of a customer. However, to attain the most value added, the best solution should be selected not only based on customer's requirements, but also considering benefits of the proposed alternative from a long-term perspective. For that reason, solutions should be assessed in terms of costs and environmental impact along the whole product lifecycle, which involves the definition of the LCC/LCA ratio [63]. In order to perform LCC/LCA analysis, simulation tools (e.g., Product Lifecycle Optimization tool) supported by the Leap platform are deployed to reduce a number of optimal solutions, and thus optimizing time required to make a decision [52].

Generally, LCC value represents a sum of four elements, namely acquisition cost, operating cost, maintenance cost, and conversion/decommission cost [63]. Accuracy and reliability of the defined LCC value highly depends on the availability of related information. Therefore, it is critical to ensure that all stakeholders working on LCC analysis attain up-to-date information.

The last layer concerns data sources, which corresponds to collection of documents, CAD models, and various databases [53].

A general structure of Leap includes two key bundles: Knowledge Exploitation Bundle and QLM. The former, in turn, consists of LCC/LCA service that processes lifecycle data, defines and optimizes the intended performance; and Chart-based reporting service that is responsible for displaying data from the LCC/LCA service, as well as creating, managing and sharing reports. As for QLM, it represents a communication standard that enables information capturing and thus supports a decision-making process [11].

Since LinkedDesign supports data federation and its exchange between different stakeholders, data integration holds the project's significant attention. LinkedDesign mainly focuses on integration of heterogeneous data from sources to a single database, which creates a holistic view on data and prevents possible data duplication. Therefore, it is critical to provide a standardized way to data presentation as well as to enable its accessibility and processing capability [79]. QLM MI is a flexible communication interface that supports exchange of heterogeneous product information between Leap components and nodes [43].

The Leap platform has been tested by three large global enterprises, namely Comau, Aker Solutions and the Volkswagen Group. However, all three companies pursue different targets that specify features and functionalities of the platform.

Comau is a global organization, which business focuses on providing process automation solutions [79]. Within the Comau case, the project's objective is to improve lifecycle cost calculation. For this goal, Leap aims to federate product data related to LCC analysis (including customer's data and requirements) and to provide the unified access to the integrated data throughout the whole product lifecycle.

Aker Solutions is one of the global leaders in the gas and oil industry, which provides engineering service/product solutions and technologies [79]. Aker Solutions aims to deploy Leap in a design phase in order to improve collaborative sharing and reuse of knowledge across multiple distributed teams working on multidisciplinary projects. Furthermore, Leap should support automatic design solutions, that is, the capability to automate design routine activities [53]. Consequently, benefits from the platform are cost reduction and higher quality decisions on operational and managerial levels.

The final use case concerns the Volkswagen Group, which represents a leading global manufacturer on the automobile market [79]. The focus of LinkedDesign in this case lies on improvement of production quality and quality management by means of optimized process reliability. Therefore, Leap is used to unify collection of data in different data formats to monitor the process quality and to define production defects as well as their causes. This means that the platform intends to support the following services: failure detection, failure analysis and process adjustment [79]. In addition, the Leap's critical aim is to enable data sharing across different departments of the enterprise.

5.3.3. Evaluation against the DIGIBUILD approach

The overall aim of the LinkedDesign project is development of the integrated information system (Leap) to enable federation of data in different formats and from different sources in order to enhance user-centric lifecycle information management in design and production phases.

In a design phase, Leap is deployed in two use cases. The first use case is dedicated to provision of LCC/LCA analysis, that is, the Comau scenario. The outcome is improved design efficiency and sustainability. The second case is the Aker Solution scenario. Aker Solution employs Leap to share and reuse knowledge obtained in previous projects. Thus, the goal of LinkedDesign is to enhance collaboration between stakeholders and to enable automatic design in order to reduce costs and time required to make decision as well as improve their quality.

In a production phase, Leap application refers to the Volkswagen Group case. Leap, in assistance with the Trimek tool, enables monitoring of the production process. The aim is to improve quality management and reliability of the manufacturing process.

Although LinkedDesign mainly focuses on data management rather than performance management, the approach and concepts of this project can contribute to the problem of cumulative performance improvement. Hence, LinkedDesign is evaluated further against the DIGIBUILD approach.

Performance monitoring & Gap revealing

In order to ensure high quality of the production process, it is critical to monitor continuously the condition of operating machines and equipment. For that reason, Leap supports services that monitor in-line quality of assets by means of capturing relevant data from the production line [79]. This requires installation of sensors into the machine. Thereupon, using the Dialog service, Leap retrieves data from the sensors and sends it to the PLM Data Service, which, in turn, attaches transmitted data to the related products. Further, analyzing product design specifications, a production manager can compare the actual and the intended product performances in a single place and identify whether a product has any defects.

Performance gap revealing, in this case, improves design and production in terms of efficiency and timesaving in recognizing a problem and its causes in the initial design or production, and in modeling an alternative problem-solving solution based on benchmarking the actual and the intended performances.

Performance modeling

In the LinkedDesign project, performance modeling mainly concerns the provision of LCC analysis. Calculating LCC value is crucial in order to develop an efficient solution for a customer. Although a designer usually conducts LCC analysis in a proposal phase, it is also essential to calculate LCC during the whole product lifecycle. LCC analysis facilitates optimization in decision-makings and resource allocation.

Leap assures continuous collection and integration of all data related to LCC calculation and enables designers to easily model and stimulate alternative design and engineering solutions.

Benchmarking

Considering the Aker Solutions scenario, LinkedDesign concerns and implements the benchmarking process, namely internal benchmarking. Generally, benchmarking means that a company analyzes its current product or process; defines the available best solution; and compares both of them. Thereupon, the company obtains understanding on what and how should be improved, and adjusts its solutions and processes according to this knowledge. Hence, this complies with the LinkedDesign proposal.

Leap supports the KBE approach providing capability to acquire and store knowledge and experience from the previous projects and reuse it later [79]. Therefore, it facilitates design based on already performed projects' success, but taking into account previous problems and failures either. Consequently, this decreases required time and efforts to define design problems and inconsistences, and thereby improves quality of design.

Solution proposal

Concerning a design stage, Leap supports automatic calculation of LCC items for each solution [63], which enhances reliability and time-efficiency of solution proposals development. Furthermore, LCC/LCA service facilitates an adaptive decision-making process by processing and linking product design to information captured during the whole product lifecycle [79]. Finally, Leap supports collaboration among project stakeholders providing a communication channel to discuss all project-related issues in order to understand better demand and requirements of customers, as well as ideas and concepts of designers. As a result, this significantly improves quality of the proposed solutions.

5.4. ESCO example

5.4.1. Principles of ESCO

The current emphasis on controlling the environmental impact (e.g., decrease in CO_2 emissions) and increase in energy prices has led to the growing interest in new and efficient approaches to control of energy consumption. One of the modern and becoming more popular approaches is ESCO (Energy Service Company). ESCO represents a company (usually private and profit-oriented), which provides turnkey energy services aiming at optimization and improvement of energy efficiency of facilities. Achieving energy efficiency is crucial, because the ESCO reward directly depends on the energy savings. As such, this raises the criticality of accurate energy measurement and energy savings verification. IPMVP (i.e., the International Performance Measurement and Verification Protocol) is an instrument recommended by the European Commission DG JRC to support a measurement and verification process and to enhance understanding on risks allocation and management [18].

Another group of companies offering energy-efficient services is ESPC (or, Energy Service Provider Company). For example, ESPC provides such services as the supply and installation of energy-efficient equipment, building refurbishment, maintenance and operation. The difference between ESPC and ESCO lies on a reward system. While ESCO is paid for the results (that is, the energy savings), ESPC charges a fixed fee for their equipment or service. Therefore, for ESPC there is no risk in a case of underperformance.

EPC (i.e., Energy Performance Contracting) is a form of the ESCO contract, which defines a level of energy efficiency improvement, as well as the means of its monitoring and verification during the whole service provision. The payment terms should be also established explicitly in a contract. Depending on the distribution of investments, savings and risks, there are two sub-forms of EPC, namely shared savings and guaranteed savings [12].

The shared savings assume that ESCO performs financing and attains a share of energy costs savings in return. This share of savings is not fixed and is dependent on the terms of a contract: its length, payback time and risks. Generally, this model is attractive for ESCO developing markets, because there is no financial risk for clients, and therefore this stimulates them to use ESCO service.

Comparing with the shared savings, in the guarantee savings a customer is responsible for financing (i.e., paying for services of the contractor), and ESCO assures a certain level of the energy savings, that is, takes all performance risks from a customer [18].

Despite EPC, there are other types of ESCO contracts, for example [12]:

1) 'First out' approach – ESCO obtains all energy savings until project investments and ESCO profit are fully reimbursed. As such, the length of a contract depends directly on the energy savings;
2) 'Comfort contracting' – ESCO covers not only energy services, but also facilitates maintenance services (e.g., by assuring the comfort level and the healthy indoor environment). This approach is widespread in the Nordic countries;
3) 'Delivery contracting' – focuses on outsourcing energy services. One of the forms is chauffage contracting, which has received the most interest in recent years. Pursuing this approach, ESCO has the strongest stimulus to provide services in the most efficient way, because its earnings directly depend on the energy efficiency improvement. The customer's existing bills for energy use minus a set guarantee in the monetary savings define a

service fee. This type of contract is usually very long (20-30 years), where ESCO is also responsible for maintenance and operation during the contract.

The main driver to use the ESCO model for both sides is financial benefits. Customers optimize energy consumption, and therefore reduce their bills. Service providers, in turn, raise their profit by producing significant energy savings. Thereby, the market forces, like the increasing energy costs and taxes, lead to the growing interest among clients, thus driving the ESCO market to flourish. Furthermore, governments of most developed countries focus on promoting sustainable development and decreasing the environmental impact. Therefore, they support the ESCO market by developing associated research programmes and legislation.

Generally, ESCO is beneficial in many aspects, for example: assuring energy efficiency improvement; increasing health and comfort of facility occupants; improving building lifecycle value; and finally, facilitating the societal prosperity and the public image.

However, despite all benefits of the ESCO model, it is not widely employed globally. The main reason is lack of comprehensive definition of the ESCO concepts and business. Hence, clients do not clearly understand benefits of the ESCO model, and as a result, there is not trust between the clients and ESCOs. In addition, ESCO is associated with high transactional costs. In order to attain benefits from the ESCO model and receive high return on investments, a customer should consider ESCO from the long-term perspective. Moreover, although monitoring and verification of the energy savings is critical, there is still lack of proper monitoring and verification practices. Finally, inappropriate (that is, rapidly changing) legislation hinders the growth of the ESCO market, because it is highly challenging and risky to comply with long-term ESCO contracts in such circumstances [12].

Because buildings produce most energy consumption and emissions, this sector is becoming one of the critical customer target group for ESCOs. Currently, there are various initiatives and pilot projects inside the residential sector.

5.4.2. TOPAs project, objectives and values

Buildings represent a large source of energy consumption as well as a significant producer of greenhouse gases [46]. Therefore, improvement in energy efficiency and reduction of the environmental impact form the critical concerns within EU research field, which encourages productivity and innovativeness of the European economy and market. According to the European development strategy, ‘Horizon 2020’, around 60% of research budget supports sustainable development, namely investigation and development of innovative solutions that decrease the environmental impact (e.g., reduced carbon footprint by 20%), enhance the economic prosperity (for example, increase in efficiency of energy consumption by 20%), and assure health and comfort of building occupants [28].

EeB-07-2015, which topic is “New tools and methodologies to reduce the gap between predicted and actual building energy performances at the level of buildings and blocks of buildings”, is a call for proposals of projects in the field of Energy-efficient Buildings (EeB). The objective of this initiative is to develop new and innovative methodology to monitor and assess the actual energy performance of buildings and identify the existing EPGs (i.e., energy performance gaps), as well as its causes and consequences [23]. This helps to calculate building energy consumption over the whole building lifecycle more accurately. The achievement of this goal requires the development of energy monitoring and evaluating methods and tools like performance indicators, sensing technologies and data analysis methods. Eeb-07-2015 assumes development of an online interactive platform, which collects data on the actual performance from the delivery and operation phases. Feedback obtained from the online platform facilitates the adjustment of a corrective actions plan to close a gap between the intended and the in-use energy performances. The initiative, overall, focuses on developing an intelligent energy management system, which optimizes energy demand and supply in real time [17, 23].

TOPAs (the Tools for cOntinuous building Performance Auditing) is an ongoing project launched under the acronym EeB-07-2015. The project was started in November 2015 and its duration constitutes 36 months.

The project focuses on providing understanding on a gap between the intended and the actual energy performances, and reducing the EPG to 10% [73]. Identifying both the EPG and its causes is crucial, because it enables to correct and adjust energy plans and activities. Consequently, this decreases costs by means of producing up to 20% of the energy savings, improving occupants' health and comfort issues, and encouraging buildings sustainability in general.

TOPAs aims to develop a holistic performance-auditing framework implemented in a cloud-based platform and consisted of decision support tools and analytic methodologies, which support continuous monitoring of energy performance on an operational level [73]. In addition to measuring energy consumption, TOPAs evaluates air quality and the environmental state. The main target user groups are building owners, facility managers and energy saving companies (ESCOs).

Generally, the research plan includes the performance of the following steps [74]:

- Defining technical and functional requirements as well as architecture of the TOPAs framework by analyzing current industry needs and best practices in the area of performance monitoring solutions;
- Identifying EnPIs (or, Energy Performance Indicators) that enable monitoring and evaluation of the building energy performance;
- Creating a platform for performance monitoring across multiple buildings by implementing an open BMS (Building Management System) approach;
- Developing complex models for continuous performance prediction taking into account energy usage, indoor air quality, occupants behavior and equipment effectiveness;
- Implementing DMPC (i.e., Distributed Model Predictive Control) –a system

that supports optimization of energy management by changing model and controller parameters in order to balance power demands and to minimize the EPG;

- Exploiting new and enhanced decision support tools to reveal stakeholders benefits in terms of cost reduction and improved indoor air quality;
- Evaluating the TOPAs concepts and solutions in three test cases – IBM Campus in Dublin, Ireland; CIT Campus in Cork, Ireland; and Galeo Building in Paris, France.

5.4.3. Evaluation against the DIGIBUILD approach

TOPAs, as being a part of EeB-07-2015 initiative, focuses on the problem of revealing an energy performance gap (that is, the discrepancy between the intended and the actual energy demand) and identifying causes and consequences of this gap. The project aims to support ESCO principles, thus promoting the importance of monitoring both the energy use and the environmental and air quality in a building's operation phase. To enable this goal, TOPAs develops a set of analytic tools and methodologies, which help to monitor and model energy performance and facilitate corrective decision-making in real time. This should produce significant increase in energy efficiency, as well as assure comfort and healthy conditions for occupants living or working in a building.

TOPAs does not support all elements of the DIGIBUILD approach, but concerns most of them. Overall, both projects pursue similar approaches and goals to performance auditing and performance gap revealing.

Performance modeling & Performance monitoring

A problem of the current performance auditing is that it is the one-off process, which is carried out at a specific point of time and has the limited duration. Because factors influencing on energy demand and consumption can vary over time (e.g., due to changes in weather conditions), a single performance audit does not provide accurate and reliable results. The problem solving is continuous performance auditing, where stakeholders can attain a detailed report on constantly measuring energy performance in order to adjust their energy management plans and minimize the EPG [71].

TOPAs focuses on developing tools that both measures the actual performance and maintains models for continuous performance prediction. Modeling and monitoring tasks are integrated into one platform, which is designed under the open BMS approach, to reveal a gap between the prediction and the current state of performance in real time. In addition, the project aims to develop performance indicators, called EnPIs, to facilitate measurement and sharing of the ongoing performance.

Gap revealing & Exploring improvement opportunities

Collecting data on the actual and the intended energy performances in the integrated BMS platform enables analysis of an enormous amount of energy-related data and identification of performance gaps, that is, exploring areas for improvement. Using machine-learning techniques, the platform facilitates the adjustment of performance prediction models to close the EPG and as a result, supports adaption of energy management plans by correcting the parameters in models and controllers in order to comply with the dynamic building environment [74]. Finally, revealing a performance gap, the platform assists in defining the potential of the energy savings and improvement in the occupants' comfort level, as well as makes performance faults visible.

Performance-focused business model

TOPAs focuses on continuous performance auditing, which assumes the continuous flow of energy performance information (including building users behavior) provided by facility managers, building owners and occupants. Acquiring and analyzing this information, energy service providers can enhance their services in order to optimize energy performance and minimize the EPG. Such process facilitates a performance-focused business model.

Moreover, TOPAs supports ESCO principles, which initially assumes sticking to the performance-based contracting. This means that the payments depend on the provided value to clients, namely the energy savings. Finally, according to the ESCO model, a service provider and a customer share either performance or financial risks, which is also a critical aspect in the DIGIBUILD proposal.

Chapter 6. Discussion

This chapter revises the findings of chapters 3-5 and presents the results according to research questions. In addition, the chapter discusses the limitations of research.

6.1. Main findings

6.1.1. RQ 1. How and why revealing a gap between the potential and the actual performances will affect the overall improvement of lifecycle value of buildings-in-use?

Sustainable development is a main facilitator of cumulative improvement of buildings lifecycle. Currently, sustainable development is not widespread in the construction industry. The reason is low demand from customers, who avoid purchasing innovative and unexperienced solutions because of unclear benefits and risks. Thereby, solution developers (including designers and engineers) are not interested in sustainable solutions and as a result, create products and services that are price-oriented and explicitly expressed by customers. However, customers often do not understand what they really need, or which solutions available on the market would improve the overall building performance in the most effective way.

Performance gap revealing encourages sustainable development by introducing a performance-focused business model. Performance-focused business model assumes value-based development, that is, promotion of the best value added solutions. A performance-based approach assumes value co-creation, which requires close cooperation between developers and customers. In the proposed approach, the customers are suppliers of the information about the actual asset performance. Integrating this information with a predicted model, solution providers can make an effective value proposition supplemented with lifecycle analyses like LCC and LCA. Therefore, a customer gains the understanding on how the proposed solution achieves a sustainable building target and closes the building-related gap, as well as what are the associated costs, risks, and benefits in a long term.

The performance-based approach stimulates development of more expensive, but more reliable and higher quality products and services, because the procurement is based on performance, rather than price. The gap revealing process facilitates continuous performance auditing, which represents a useful tool to verify performance outcome and created value. Furthermore, it assumes considering various aspects of building performance, thus providing a critical holistic view on performance improvement.

6.1.2. RQ 2. What tasks should be performed to reveal the building performance gap?

Chapter 5, namely a 'DIGIBUILD project' section, presents the process of gap revealing, and Chapter 3 and 4 discuss each task related to the process in more details, including its benefits, obstacles, attendant goals and practices. Summarizing analyzed information, the following tasks can be defined:

1) *Performance monitoring* facilitates provision of information on the actual asset performance. This can be done by means of the Internet of Things. In order to monitor the performance of buildings, special sensors and other smart objects should be firstly embedded into the assets. The sensors support automatic data collection and processing. Moreover, because data gathered from the smart objects is heterogeneous, this requires establishing a standardized communication protocol, thus enabling interoperability of the objects.

2) *Performance modeling* is responsible for defining the intended performance level, conducting risk analysis, LCC/LCA calculations, adjustment of lifecycle operation and maintenance plans. This assures meeting the performance requirements determined by a customer and building regulation (e.g., comfort, safety, economy, environmental impact). The task requires development of analytic and simulation tools, as well as integration of all related data in a common platform.

3) *Performance evaluation* relates to measurement of performance aspects, which

leads to performance gap definition. This task involves determination of performance indicators and their interaction between each other. It is also critical to identify reference targets of the indicators to enable gap revealing and support exploration of improvement opportunities.

4) *Exploration of improvement opportunities (benchmarking)* assumes continuous performance improvement by comparing performances and identifying the best value added solutions. It encourages the compliance with the best practices available on the market, thus promoting sustainable development. However, in order to enable comparison of performances and benchmarking against other building products and services, performance indicators should be presented in a standardized form. Furthermore, it is essential to assure a functional equivalence of the compared solutions.

5) *Solution proposal* requires movement towards value-based development and sales.

The thesis mainly focuses on functional characteristics and tasks. However, technical aspects should be also taken into account. Since the DIGIBUILD approach assumes comparison of the actual and the intended performances, that is, integration of performance monitoring and performance modeling, this makes data integration being a critical task. Moreover, it is essential to ensure dynamic and efficient data storage and retrieval. Finally, it is required to organize and provide simple but powerful communication and networking capabilities enabling information exchange and sharing across building stakeholders.

6.1.3. RQ 3. Where performance gap identification has been already implemented in practice?

The thesis analyzes three EU projects (i.e., PERFECTION, LinkedDesign, and TOPAs), which contribute to the problem of performance gap revealing from different prospects.

PERFECTION is rather old project, which was conducted in a period of 2009-2011.

The project focuses on development and implementation of a performance assessment framework, which enables evaluation of buildings performance and potential solutions in a structured way. Performance evaluation is an important step required to identify a performance gap. Performance gap identification is a process of comparing the intended performance with the actual one. The reliable comparison is impossible without creating a standardized framework of performance indicators. PERFECTION provides a comprehensive study on performance indicators for evaluation of indoor environmental quality, as well as defines assessment methods for each performance indicator.

Furthermore, the actual performance of buildings is presented in a form of assessing performance indicators by a letter (A is the highest performance level and E is the lowest one, respectively). The intended performance in this project relates to the target value of KPIs, that is, 'A class'. Thereby, such approach to gap revealing is rather static. It shows whether the considered performance indicator is low, but it does not explain why (i.e., what problems exist and what are their causes).

Generally, gap revealing facilitates exploration of improvement opportunities. In the PERFECTION project, this process is manual. Solution providers can specify from 1-3 of performance indicators, which their solutions focus on and can enhance. Thereupon, providers should request information on buildings, where the specified indicators are low. Hence, the proposed approach supports value-based development, which is a critical prerequisite of sustainable development.

Comparing with the PERFECTION project, TOPAs focuses on automatic exploration and exploitation of performance improvement opportunities. Gap revealing, in this case, is a continuous process and concerns comparison of the actual energy consumption with the predicted one. The result of comparison is the automated adjustment of model parameters and controllers, thus increasing energy savings. TOPAs supports an ESCO business model, which is performance-oriented. According to ESCO principles, the energy savings is the basis for service providers' reward. Therefore, TOPAs facilitates value-based development, that is, provision of services that minimize an energy performance gap, and thereby, increase the providers reward.

TOPAs aims to develop models, methodologies and tools, which enable analysis of performance information and support a decision-making process. This can be an interest for DIGIBUILD project. However, the TOPAs project has been just started, and there is not public information on development and implementation yet.

Finally, LinkedDesign can contribute to the DIGIBUILD proposal by providing information on technical and functional aspects of data collection and processing. Because gap revealing initially relates to capturing an enormous amount of heterogeneous data from different data sources (e.g., various sensors and measures), LinkedDesign is an important project to analyze. The project investigates a set of methodologies and technologies applied in data integration and shows their application in several case scenarios. Although the project focuses on product design and manufacturing, its concepts and ideas can be deployed in the building industry as well.

6.1.4. RQ 4. What are key factors that make the process of revealing the performance gap challenging?

Performance gap revealing relates to value co-creation, that is, requires acquisition of information from customers. However, customers often do not want to make information on assets public. Several papers as well as two analyzed projects define information sharing as a considerable challenge that can be a barrier towards value-based development. Stakeholders can avoid information sharing because of lack of trust, or if performance information presents any competitive significance for an asset owner. Furthermore, value co-creation raises interdependence between stakeholders, which most companies prefer to avoid.

The process of performance gap revealing, proposed in the thesis, is innovative. As any innovation, it is unclear and requires changes in organizations thinking (i.e., a shift from transactional to strategic thinking). Since customers usually feel skeptically about innovative solutions, there is high need for promotion activities to enhance the market demand. However, the construction sector is known as having weak marketing and promoting strategies.

In addition to changes in a way of thinking, innovative technology or methodology require time to understand the proposed concepts, as well as advanced skills and competence from the building stakeholders. Moreover, performance gap revealing assumes application of specific information systems and technology, which leads to additional expenditures.

In order to monitor, model and compare performances, there is need to define performance indicators. However, it is rather challenging to calculate the optimal number of performance indicators. It is impossible to take into account all aspects of building performance that can be monitored or measured, but a number of KPIs should be sufficient to develop solutions that close the specific gap and improve (at least, do not affect negatively) the overall performance.

Finally, in countries with the rapidly changing legislation, it is difficult to stick to long-term contracts. However, performance gap revealing requires a shift from a project-based to performance-oriented business model, which implies long-term cooperation between stakeholders.

6.2. Limitations

This study has several limitations. First of all, the empirical findings are based only on public sources, that is, projects' websites and the deliverable documents. This approach provides restrictions on analyzed information, because it does not allow obtaining additional explanations on concepts or research details, as can be done, for example, in interviews, where there is a dialogue between a researcher and an interviewee. Furthermore, collected information enables only qualitative analysis, which is less reliable than a quantitative one.

Moreover, rather limited information was found on implementation results, that is, successful and failed implications of the projects. Therefore, it is difficult to verify whether the project proposal brings the expected benefits to stakeholders in practice. This discourages the validity of this research.

Finally, one of the projects has been recently started, which leads to lack of information and details on project's tasks and deliverables. Thereby, this is hard to evaluate its potential implications for the DIGIBUILD approach.

Chapter 7. Conclusions

Sustainability refers to improvement of one or several aspects of the societal prosperity, from health and well-being of residents to environment and resource efficiency; and it has become a critical issue in European vision and development strategy. Performance is an important measure that defines how well sustainability goals have been achieved. Hence, it led to the movement from a prescriptive to performance-based approach, which assumes a shift from price-oriented to value-based development.

The building industry is a sector, where a price has been a major criterion in selection of contractors for a long time, thus promoting development of the cheapest solutions, which usually are not productive in a long-term perspective. This has resulted in cumulative recession of buildings lifecycle value, and thus declining the building ecosystem and the societal prosperity in general.

The solution is to focus on value-based development, that is, stimulate implementation of products and services that bring the best value added to a facility, taking into account the overall performance improvement as well as long-term costs and benefits. Performance gap revealing enables value-based development by making building problematic areas visible, thereby encouraging to design such solutions that close the specific performance gaps.

The thesis investigates the research problem from two prospects – reviewing the existing literature and analyzing the related EU projects.

The study presents a framework that describes the phases required to leverage value-based development. The framework is based on the concepts proposed by the DIGIBUILD project, which focuses on improvement of buildings lifecycle value by digitalizing a performance-focused business model.

Generally, the concepts of a performance-based approach (including procurement, contracting, regulations, design and maintenance) are thoroughly presented in the literature. This enables to invent the initial understanding on the main drivers towards value-based development. Furthermore, performance gap revealing requires implementation of digital solutions to enable data collection, integration, processing, and decision-making. Therefore, the thesis also analyzes modern technologies and methodologies that facilitate performance gap revealing tasks (i.e., monitoring, modeling, assessment, benchmarking).

Finally, the study evaluates three existing projects, which consider different aspects of the performance gap revealing process, and thus enhancing understanding on the research problem. However, this thesis does not concern technical aspects (e.g., implementation requirements or architecture), which can represent a focus for future research.

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Appendix A. Performance indicators framework

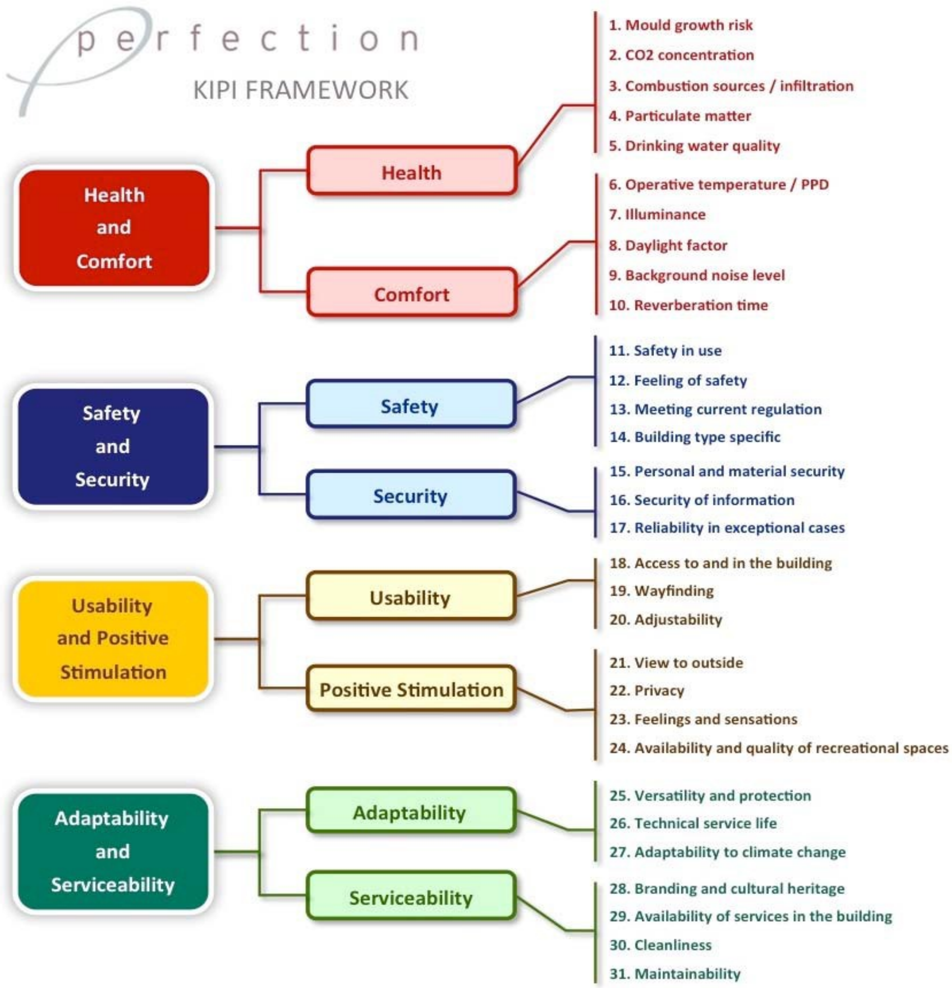

Figure A.1. KIPI framework (Source: [17])

Appendix B. Example of indicators weighting

Health and comfort			
Indicator name	**Comments**	**Grade**	**Weight**
Mould growth risk (Health)	-	C	3.6 %
Ventilation / CO2 (Health)	-	C	4.2 %
Combustion sources / infiltration (Health)	-	C	3.2 %
Particulate matter (Health)	-	C	3.1 %
Drinking water quality (Health)	-	A	3.4 %
Operative temperature / PPD (Comfort)	-	C	3.8 %
Illuminance (Comfort)	-	C	2.9 %
Daylight factor (Comfort)	-	D	3.6 %
Background noise level (Comfort)	-	C	3.2 %
Reverberation time (Comfort)	-	C	1.8 %

Figure B.1. Indicators weighting (Source: http://cic.vtt.fi/kipi/showcase.php?project_id=153)