Intelligent Buildings International

ISSN: 1750-8975 (Print) 1756-6932 (Online) Journal homepage: https://www.tandfonline.com/loi/tibi20

State-of-the-art of intelligent building envelopes in the context of intelligent technical systems

Jens Böke, Ulrich Knaack & Marco Hemmerling

To cite this article: Jens Böke, Ulrich Knaack & Marco Hemmerling (2019) State-of-the-art of intelligent building envelopes in the context of intelligent technical systems, Intelligent Buildings International, 11:1, 27-45, DOI: 10.1080/17508975.2018.1447437

To link to this article: https://doi.org/10.1080/17508975.2018.1447437

INTELLIGENT BUILDINGS INTERNATIONAL
2019, VOL. 11, NO. 1, 27–45
https://doi.org/10.1080/17508975.2018.1447437

State-of-the-art of intelligent building envelopes in the context of intelligent technical systems

Jens Böke[a], Ulrich Knaack[b] and Marco Hemmerling[c]

[a]Architectural Engineering + Technology, Faculteit Bouwkunde, Technische Universiteit Delft, Delft, Netherlands; [b]Architectural Engineering + Technology, Technische Universiteit Delft, Delft, Netherlands; [c]Cologne University of Applied Science, Cologne Institute for Architectural Design, Cologne, Germany

ABSTRACT
The high and increasing requirements concerning energy consumption and the interior comfort of buildings result in a demand for more efficient façade constructions. In its role as a mediator between the exterior and interior of a building, the façade takes on a multitude of functions with effect on the building's performance. Intelligent façades offer higher performances compared to static constructions, achieved by dynamic adjustments to changing environmental influences and interior requirements. Such systems are being explored and already applied. The concept of intelligent façades exists since the beginning of the 1980s. Since then, the technological possibilities for the implementation of intelligent systems have multiplied. Today, the fourth industrial revolution is based on the implementation of intelligent and networked production facilities. Considering the current exploration of intelligent technical systems in the industry, the understanding and the demands on the intelligence of a system change. The aim of this study is to examine the comprehension of an intelligent system in the context of the façade and in the context of the industry. This is to provide the basis for subsequent research on the transferability of strategies. The study provides used terms, relevant aspects, current definitions and characteristics of the respective intelligent system.

ARTICLE HISTORY
Received 24 April 2017
Accepted 21 February 2018

KEYWORDS
Intelligent façades; adaptive building envelopes; intelligent technical systems; industry 4.0; cyber-physical systems; literature review; state-of-the-art

1 Introduction

1.1 Background

The façade mediates between the exterior and the interior of a building. In this role, it is faced with continuously changing conditions. These include changing climatic influences from the outside, variable needs depending on occupancy and user preferences inside (Knaack et al. 2014). In its main role as a separation and filter layer, the façade adopts a range of protection, control and regulation functions (Herzog, Krippner, and Lang 2004). In the current development, the functional scope of the building envelope is further expanded by the increasing integration of building services (Klein 2013). The façade has a significant influence on the interior comfort and the energy consumption of the building. We place high and continuously growing demands on both aspects and thus on the performance of the building envelope.

CONTACT Jens Böke J.Boke@tudelft.nl Technische Universiteit Delft, Architectural Engineering + Technology, Faculteit Bouwkunde, Julianalaan 134, 2628 BL Delft, Delft 2600 AA, Netherlands

Supplemental data for this article can be accessed at https://doi.org/10.1080/17508975.2018.1447437

The origin of façade constructions can be seen in massive walls that humans used to protect themselves from cold climates, and in lightweight structures like tents that provided mobility. The understanding of the façade derives from the functional separation of the hull from the buildings structure. The 'building envelope' and 'building shell' are alternative terms and refer to the façade as such. There are also designations which aim at a special construction principle. In view of an extended functional scope and increasing demands on the building envelope, the development of new technical possibilities has also led to new types of façade construction. The terms 'curtain wall' or 'double-skin façade' are examples of such specifications (Knaack et al. 2014). For a long time, planners and engineers understood the building envelope as a barrier, with an attempt to shield the interior from the influences of the external space. As an integral part of this concept, building services manufactured the interior climate independently of external conditions (Addington 2009). The performance of a building envelope was measured by how well it protected the interior from the influences of the external environment. This strategy is now extended by the concept of adaptive building envelopes (Favoino, Jin, and Overend 2014). Adaptive building envelopes respond dynamically to changing conditions and requirements. They utilise climatic changes, and thus reduce the energy consumption for the maintenance of the interior climate of a building. There are a number of realized adaptive building envelopes. Examples such as the Al Bahr tower in Abu Dhabi or the Kiefer Technik Showroom in Bad Gleichenberg usually address individual adaptive functions (Fortmeyer and Linn 2014; Schumacher, Schaeffer, and Vogt 2009). The development and implementation of adaptive façade concepts are in the beginning stages (Aelenei et al. 2015). One challenge is the multi-functionality of the façade. Its features are interdependent and partly mutually exclusive. According to Loonen, the pure addition of individual adaptive features does not automatically lead to an increase in its operability and performance. He states the need for inter-coordinated adaptations that also involve subsystems and building services. The negotiation of individual adaptive façade functions results in the need for an intelligent decision-making in the control of the façade's adaptations (Loonen et al. 2013). Within the building industry, the notion of intelligence is not new. The term was used liberally in the past and its understanding has changed with the progressive development of new technologies.

The rapid developments in information and communication technologies (ICT) over the last decade created the technical basis for the current implementation of an industry 4.0. This refers to the transformation from automated to intelligent manufacturing. After the mechanization, the use of electricity and the application of information technologies, the implementation of cyber-physical systems (CPS) represents the fourth major development step in industrial production (Kagermann, Wahlster, and Helbig 2013). The German government established the term industry 4.0 by using it in the high-tech strategy 2020 in accordance with the so-called fourth industrial revolution (Oesterreich and Teuteberg 2016). In addition to the development of smart products and augmented operators, it involves the realization and networking of smart machines (Weyer et al. 2015). These intelligent technical systems are intended to make industrial production faster, more efficient and more flexible, thus ensuring the competitiveness of companies. The building envelope can be understood as a system of its components. The components must co-operate for multi-functional operability of the façade according to the assets in the industrial production chain. It is assumed that strategies and concepts for the control and organization of adaptive façade systems can be derived from industrial intelligent technical systems to the benefit of the building performance.

1.2 Problem statement

The scientific discussion about the understanding of an intelligent façade, but also of an intelligent technical system in the industry is not concluded. It is unclear how the term intelligent is recently defined as it relates to the building envelope, and whether it meets the current understanding of an intelligent system in the industry. In order to be able to draw insights from the implementation of intelligent technical systems for the transmission to the building envelope, a so far non-existent list of preconditions and criteria of such systems is required. At the same time, information is missing about which technical requirements and criteria of an intelligent system the façade already fulfils.

1.3 Research question

The main question of this study concerns the understanding of an intelligent system in façade engineering and in the industry.

- What are existing definitions and key aspects in intelligent façades and in intelligent technical systems?

  The following sub-questions specify the formulation of the main question.

- How are intelligent façades defined?
- Which requirements and subdomains of intelligent façades can be identified?
- What are the criteria for an intelligent façade?
- How are intelligent technical systems defined?
- Which requirements and subdomains of intelligent technical systems can be identified?
- What are the criteria for an intelligent technical system?

The investigation aims to clarify the understanding of the concept of intelligence for the particular topic. It pursues the following objectives:

- To discover existing definitions for intelligence in building industry and in manufacturing industry;
- To identify aspects and criteria for a system being intelligent in both fields;
- To highlight aspects and subtopics for further investigations.

2 Methodology

The study is based on a systematic literature review about intelligent façades and intelligent technical systems. Book publications and journal articles were examined. For an initial overview, literature was searched for the terms: 'Intelligent façades' and 'Intelligent systems'. The document titles and keywords were examined. A recognition of this first approach was their systematic composition, consisting of a descriptive property and an application. In a second step, an extended search-term matrix was created based on this organizational principle. It was used for an optimized literature search. The aim of the study is to provide an overview of previous research and definitions in both areas. To avoid detailed papers on particular aspects of the topics, the search terms were complemented with the specifications 'state-of-the-art', 'definition' and 'review'. The content-related relevance to the subject and the number of times it has been cited were criteria for the selection of an article. The matrix of search terms is attached as a table in the Supplementary appendix. The results were incorporated into a bibliographic database. Concretized literature searches were performed on individual aspects during the study. Therefore, terms of the search matrix were combined with additional foci, e.g. the term 'performance' to find contributions about the efficiency of building envelopes. The combined results of the study are thematically organized (Figure 1).

3 Intelligent façades

3.1 The façade

Regarding intelligent façades, the notion of 'skin' is significant. Origin of this designation is the analogy to the human epidermis. The human skin is understood as a whole without distinction

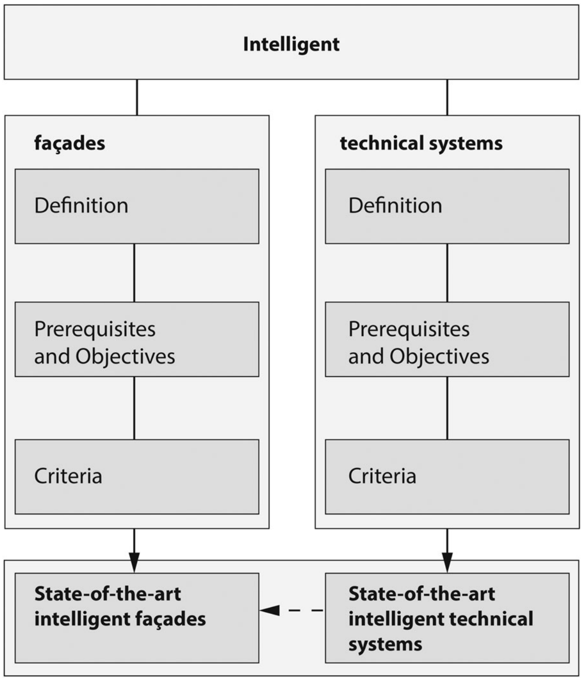

Figure 1. Methodology graph.

into components such as wall or roof, and it has self-regulating properties (Hausladen, de Saldanha, and Liedl 2008; Del Grosso and Basso 2010). It recognizes changing conditions or requirements of the body and reacts to them independently. With the term, a similar understanding of the building envelope is associated with respect to the self-regulation between exterior and interior (Wigginton and Harris 2002) (Figure 2).

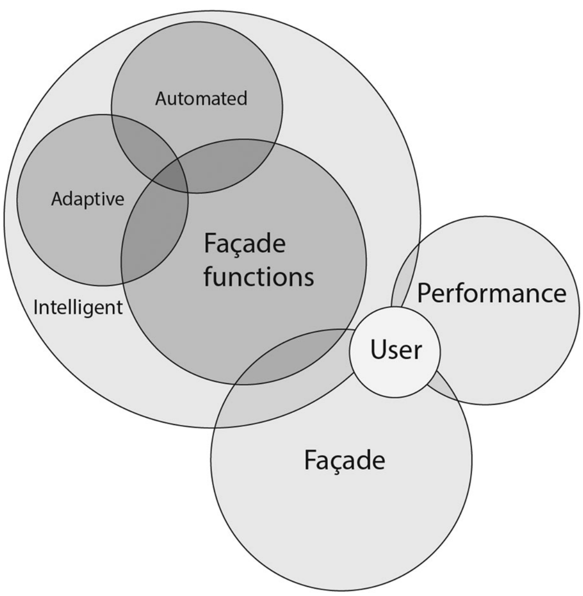

Figure 2. Visualization of the 'Intelligent façades' section context.

3.2 The addition intelligent

The term intelligent has its origin in Latin and can be literally understood as 'to choose between' ("intelligent - definition of intelligent in English Oxford Dictionaries" 2017). This generally refers to the ability to make decisions. In the building industry, the addition intelligent led to a series of misunderstandings. According to Wigginton and Harris (2002), there are over 30 definitions for an intelligent building. They state that the term should be used with caution and its meaning should be clarified for the respective context. In principle, two differing interpretations of the addition intelligent are distinguished from each other. Firstly, the term intelligent refers to an intelligent design. It is used in reference to static structures that represent an intelligent solution because of their advanced conception in the design process. Secondly, it refers to structures that provide additional, intelligent features in the building's operation phase (Wigginton and Harris 2002).

3.3 The context of intelligent buildings

Intelligent façades are a partial aspect in the broader consideration of intelligent buildings. In order to understand the meaning of intelligent façades, the importance of intelligent buildings is clarified first. The concept of the intelligent building emerged in the beginning of the 1980s. Early approaches to define intelligent buildings were primarily based on an extensive technical equipment of the building. Kroner (1997) argues that these buildings were 'technical enhanced buildings'. Instead of the architecture, the building services became intelligent with little effect on the user comfort. He denounces the practiced separation of architecture, users and intelligent systems. From his point of view, intelligent architecture includes 'intelligent design', the 'appropriate use of intelligent technology' and also the 'intelligent use and maintenance' of the building. In the scientific field, the criticism of the plain technical understanding led to the new interpretation that an intelligent building must involve the user (Wong, Li, and Wang 2005). In his investigation of the question: 'what do we mean by intelligent buildings?' Clements-Croome (1997) comes to the conclusion that it can handle technological and social changes and is adaptable to short- and long-term human needs. The ability to adapt to user requirements and also to changing environmental conditions is an important aspect in today's understanding of an intelligent building. It must be able to react to individual, organizational or environmental requirements and to deal with changes (Yang and Peng 2001). Wigginton and Harris (2002) confirm that an intelligent building can adapt to conditions and requirements to create interior comfort with low energy expenditure. They complement the ability to learn. Next to the primary goal of reducing energy costs and providing user comfort, security and automation of maintenance are objectives of the intelligent building (Anshuman 2005).

3.4 Definition of intelligent façades

The ability of adaptation is also a central aspect in existing definitions of the intelligent façade. In this respect, it represents an interface with an arbitrating function (Sala 1994). The intelligence can be understood as an intrinsic capacity and as the ability to react to circumstances and demands, self-regulating or by means of the user (Kroner 1997). Compagno refers the intelligence of the façade to its capability of dynamic adjustments. He dissociates himself from possible definitions over applied technologies and measures the intelligence of a façade by how sustainable it uses natural, renewable energies (1999). Wigginton and Harris (2002) define the intelligent skin as an active and responsive mediator between the outside environment and the interior of a building which ensures an optimal interior comfort with minimal energy consumption. A recent definition describes the intelligent façade as the result of its individual design process, which implements its adaptability with regard to internal and external circumstances. As a result of this process, the façade has components and features that enable the designed adaptation strategies (Capeluto and Ochoa 2017). On the basis of the definitions found, it is clear that the concept of intelligence refers primarily to the adaptability of the façade. Due to possible misinterpretations, researchers and professionals in this field adopted the concept of the adaptive façade (Knaack et al. 2014). Loonen et al. (2013) introduce the term 'climate-adaptive building shells' and define it by its ability to adapt continuously and reversibly to changing requirements and influences at least in partial aspects. Adaptations may occur in short-term and long-term periods. Direct reactions to changing conditions are short-term adjustments (Sher, Chronis, and Glynn 2014). Systems with this ability are often referred to as responsive systems. Long-term adjustments imply advancement processes or an evolution-induced change over generations (Sobek and Teuffel 2001).

3.5 Automation technology

A façade that allows the changeability of its construction can be regarded as adaptive, even if no automation technology is used and the adjustments have to be initiated by the users (Meagher 2015). In this context, the designation of adaptability seems to be more appropriate. In many views of an adaptive building envelope, an automated self-regulation of the adaptations is assumed (Macias-Escriva et al. 2013). Such a self-adaptive system involves the recording of information, data processing and control, and its transference in adaptations of the construction. Important components are therefore an existing sensing system, which determines relevant information about conditions and requirements depending on the project. Furthermore, a control system processes the recorded information and transmits impulses on their basis to actuators and the actuators themselves perform the adjustments of the construction (Sobek and Teuffel 2001). Accordingly, Moloney (2011) defines the intelligence of a building envelope by the key aspects of an existing 'input system', a 'processing system' and an 'output system'. He complements the 'consideration of time' and the 'ability to learn'. Today, the technical basis for the implementation of self-adaptive constructions exists (Schumacher, Schaeffer, and Vogt 2009). In addition to the available sensor and actuator technologies, the research and development of smart materials opens up further technical possibilities (Drossel et al. 2015). The control is important as it decides on the behaviour of the self-adaptive façade system. While smart materials refer to an intrinsic control, extrinsic computer-based controls enable real-time optimization and the application of artificial intelligence (Yiannoudes 2016; Park et al. 2004). Extrinsic control can be centrally or decentrally organized (Loonen et al. 2013). According to whether a feedback evaluation of the system takes place, open-loop and closed-loop controls are differentiated (Sobek and Teuffel 2001). Evolutionary Algorithms and Artificial Neural Networks are two possibilities of a range of strategies. Evolutionary algorithms simulate generations of possibilities in which the most appropriate solution can be applied. Artificial Neural Networks enable learning abilities. They are based on testing a problem on a reference record. By matching recurring patterns, solutions of comparable problems can be transferred (Sher, Chronis, and Glynn 2014). In the study of realized intelligent systems in architecture, Yiannoudes (2016) notes that although they can map learning behaviours and respond to user requirements, they work on the basis of previously anticipated rules. As a self-organizing system, the adaptive façade is confronted with complex decision-making between interdependent functions and unpredictable scenarios. Traditional rule-based controls are therefore insufficient in the context of multi-functionality and non-linear adaptations (Loonen et al. 2013; Jencks 2015).

3.6 User orientation

The inclusion of the user is one aspect of the building envelope's intelligence. It is decisive for the acceptance of automated processes whether and to what extent users can interfere with them (Loonen et al. 2013). Research projects investigate the possible interaction between the user and the building envelope (Anshuman 2005). Also, the user's perception of automated processes plays a role. In investigating the effects of the façade automation on user comfort, Bakker et al. (2014) conclude that adaptions are perceived rather positively if they occur less commonly and restrained.

3.7 Alternative designations

In the context of intelligent or adaptive façades, a wider range of terms has been established. Some of them are alternative designations or specify the subject on partial aspects. Many of the terms are not clearly defined (Aelenei, Aelenei, and Vieira 2016). Researchers demand uniform thought models and vocabulary (Loonen et al. 2015; Aelenei, Aelenei, and Vieira 2016) (Table 1).

3.8 Objectives of intelligent façades

An increase in performance can be inferred as the main objective from many of the underlined definitions. The performance describes the degree of fulfilment of a product's relevant functions (Douglas 1996). The term is used in the understanding of a total building performance, but also with regard to the building envelope and its components. Depending on the scale of the consideration, the performance may refer to material properties, components, elements or the façade as a whole (Hartkopf and Loftness 1999). One objective of intelligent façades is on the possible energy and the associated cost savings. Traditional evaluation strategies are not effective because of the dynamic properties of adaptive building envelopes (Favoino, Jin, and Overend 2014). Loonen et al. (2017) formulate the potential of building performance simulations in response to the new requirements identified in the consideration of scales, time intervals and physical domains. A further objective is to ensure a constant and high interior comfort. This refers to the satisfaction and well-being of the user. Aspects are, for instance, thermal comfort, air quality and ventilation, acoustics and visibility (Al horr et al. 2016). The goal of intelligent façades is often formulated by combining both aspects, ensuring the highest possible interior comfort while minimizing energy consumption (Compagno 1999; Wigginton and Harris 2002). In the consideration of realized intelligent and adaptive building envelopes, the architectural expression and the orchestration of moving components can also be identified as a topic and a goal (Interactive architecture 2016). Active façades, which are exclusively based on aesthetic design goals and do not contribute to the performance of the building, are not covered by the subject of intelligent or adaptive façades (Loonen et al. 2013).

3.9 Façade functions

The necessary negotiation of conditional façade functions presents a challenge for the control strategy (Loonen et al. 2013). A comprehensive consideration of the functional scope is required to identify the relevant features of the building envelope in terms of the building performance. There are different approaches to map and to sort the functional spectrum of the façade. According to the definition of Herzog, its main function is separation and filtration between the interior and exterior space. Herzog, Krippner, and Lang (2004) divide all therefrom derived requirements into two main groups: site-specific outdoor conditions and demands of use on the inside. He designates control functions as a supplement to the basic protective function of the façade. A comprehensive list of the tasks of a building envelope is summarized in the façade function tree developed by Klein (2013). Not all features have

Table 1. Alternative designations in the field of intelligent façades.

Property	Application
Intelligent	Façade
Smart	Building Envelope
Active	Building Skin
Responsive	Building Shell
High-performance	Curtain Wall
Auto-reactive	Double-Skin Façade
Climate adaptive	
Adaptive	
Kinetic	
Dynamic	
Advanced	

Table 2. List of criteria by Kroner (1997).

Central control	Change of properties	Communication/Media	Change optical properties
Possibility of intervention	Thermo-physical Thermal resistance Transmittance Absorptance Permeability Modify colour and texture	Video Voice	Patterned glazing Remote light control Dynamic shading

an impact on the interior comfort. The compilation is divided into six overarching categories called primary functions: Create a durable construction, Allow reasonable building methods, Provide a comfortable interior climate, Responsible handling in terms of sustainability, Support use of the building and Spatial formation of façade. Hausladen et al. (2005) describe the building envelope as an interface. According to their definition, the functions of the façade are in mutual relation to each other. Meeting the individual requirements can also stand in conflict with the aims of other functions. In his chart, the functions of the building envelope arise as a consequence of the seasonally varying comfort needs of the interior and the basic factors of the external environment. There are other compilations of façade functions that are tailored to specific contexts. Within the research project 'multifunctional plug & play façade (MPPF)', a list of a total of 20 façade functions in the three categories: basic functions, power generation and supply functions was developed (*mppf - The multifunctional plug&play approach in facade technology 2015*). Also, in the study on adaptive building envelopes, a set of functions was considered as part of its characterization (Loonen et al. 2015).

3.10 Criteria and characteristics of intelligent façades

In view of the varied and partly ambiguous definitions of intelligent façades, it is assumed that the examination of criteria and characteristics provides a differentiated overview of its intelligent properties.

Kroner (1997) delivers an early list of criteria (Table 2).

In their investigation, Wigginton and Harris (2002) examine realized buildings according to the following features of an intelligent building envelope (Table 3).

Ochoa and Capeluto (2008) provide a list organized according to the existing input and output systems of the adaptive building envelope (Table 4).

Loonen et al. (2015) summarize previously researched character traits of adaptive façades in a matrix with eight categories (Table 5).

In their comparison, the lists become chronologically more complex. The number of criteria increases from a total of 12 in four categories, identified by Kroner (1997) to 45 criteria in eight categories, designated by Loonen et al. (2015). In particular, individual automated aspects of the building envelope are named, such as Temperature- or Sun controllers in the list by Wigginton and Harris (2002) or, Light- and Shading controls identified by Ochoa and Capeluto (2008). Contrary to their technology-oriented perception, Loonen et al. (2015) focus more on functional aspects such as the objective, function or the type of control. All constellations have in common that they relate primarily to the physical components, the hardware of intelligent façades. Apart from learning ability, there are no software-related criteria, such as the ability to make independent decisions based on existing artificial intelligence, or the degree of networking and communication between the automated components.

Table 3. Criteria by Wigginton and Harris (2002).

The double-skin	Learning ability	Temperature controllers	Cooling devices
Building management systems	Sun controllers	Occupant control	Electricity generators
Environmental Data	Ventilation controllers	Daylight controllers	Responsive lighting

Table 4. Criteria by Ochoa and Capeluto (2008).

Class	Category	Design variable	Sub-variable
Input elements	Sensors	No sensors	Illuminance
		Light	
		Temperature	
		Glare/Radiation	
	User interfaces	Switches	
Processing elements	Individual controls	Light controls	
		Shading controls	Type blinds
		Thermal controls	Temperature level policy
		Ventilation controls	Night ventilation
			Active ventilation
		Energy controls	
	Schedules		
	BMS		
	Synchronized controls		
	Passive buildings		
	User only		
Actuating elements	Daylight systems	Sun shading	No/Horizontal/External blinds/curtains
		Daylight redirection	No/Light shelves/Automatic blinds
	Fenestration	Glazing	Conventional
	Ventilation	Window operator	Fixed/Manual/Mechanical
		Fan ventilation	
	Cooling/Heating	Passive/Active	Orientation/Conventional

Table 5. Characteristics by Loonen et al. (2015).

Objective	Function	Control	Technology
Thermal comfort	Modulate	Intrinsic	Shading
Indoor air quality	Filter	Extrinsic	Insulation
visual performance	Prevent		Switchable glass
acoustic performance	Reject		PCM
Energy generation	Admit		Solar tubes
Control	Redirect		BIPV and solar thermal
	Collect		Shape memory
	Convert		Openings
	Interact		Kinetic systems
			Radiance
Time scale	**Spatial scale**	**Visibility**	**Degree of adaptation**
Seconds	Material	No	On-Off
Minutes	Element	Low	Gradual
Hours	Wall	High	
Day-Night	Fenestration		
Seasons	Roof		
Years	Total building		
Decades			

4 Intelligent technical systems

4.1 Technical systems

Within technical domains, the term technical system replaced different, difficult to distinguish terms, such as ‘plants’, ‘machine’ or ‘device’. The task of technical systems is to transform, store or transport materials, energy or information. Material, energy and information-based technical systems are distinguished. They include a structure and a function. Components that can be separated by an imaginary system boundary from the systems environment constitute the systems structure. The properties and interactions between the components are part of the structure. The function of the system is to transform inputs into appropriate outputs. The total of all transformations inside the system is the ‘process’ (Dumitrescu, Jürgenhake, and Gausemeier 2012) (Figure 3).

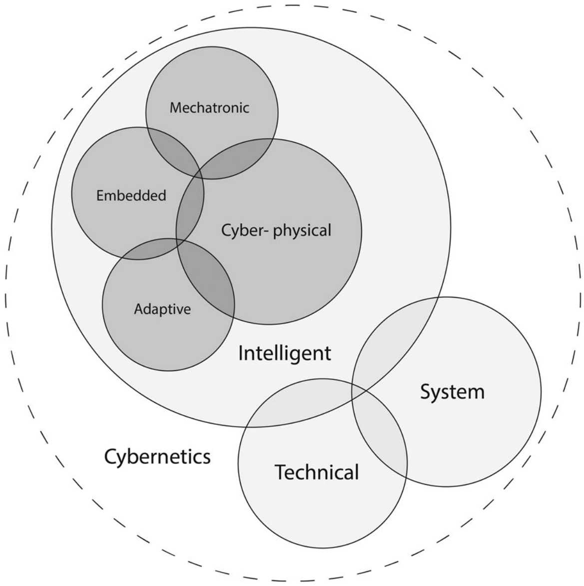

Figure 3. Visualization of the 'intelligent technical systems' section contexts.

4.2 The context of cybernetics

Against the background of comprehensive digitalization, cybernetics provides access to the interaction between human and machine and between machines amongst each other. Norbert Wiener introduced the science of control and communication under the notion of cybernetics in 1948. As a theoretical consideration of a system's behaviour, cybernetics can be applied to different application fields. They support the design of intelligent technical systems (Wiener 2013; Sher, Chronis, and Glynn 2014). A focusing of the topic has resulted in the technical cybernetics (Pickering 2015). The cybernetic system consists of an input and an output record. Interdependent system parts change over time and cause a shift in the overall system. All parts of the system are expected to pursue a uniform goal. Cybernetic systems can be classified into two orders. In the first order, the cybernetic system represents a closed-feedback circuit. The effects of the system are recorded as input values. Negative check-back indications lead to an adaptation of the system. In its first stage, the cybernetic system performs a continuous optimization with respect to a target state. Von Foerster (2003) additionally identifies the observer as an integral part of the system and thus establishes the theory of second-order cybernetic systems. He describes them as a cybernetic consideration of cybernetic systems. They provide the concept model for technical systems with intelligent properties, such as self-organization or communication (Heylighen and Joslyn 2001; Yiannoudes 2016). With reference to architecture, the relevance and transferability of cybernetics is not new. Gordon Pask formulated the demand for cybernetics and identified the interaction between space and users as a closed-feedback loop. An early and often cited example of the application of second-order cybernetic systems in architecture is the project Fun Palace by the British architect Cedric Price (*4dsocial 2007*; Frazer 1993).

4.3 The context of mechatronic systems

The term mechatronic was coined in the 1960s in Japan and consists of the two terms mechanics and electronics. Mechatronics refers to the cooperation of mechanical constructions, electronics, control and software. Due to the combination of these aspects, it is an interdisciplinary topic. Mechatronics extends the behaviour and capacities of technical systems by the integration of information. The structure of a mechatronic system is also called its architecture. Mechatronic systems consist of a mechanical structure, the so-called base system. Existing sensor devices receive information about the environment or the system itself. Also, human inputs belong to this aspect of information gathering. The collected information is processed by an 'information processing system'. The adaptation of the mechanical construction is carried out via actuators. The relationships between the different components of a mechatronic system are defined by flows. There are three types of flows: material, energy and information flows. Several individual mechatronic systems can be merged hierarchically into an overall system (Dumitrescu, Jürgenhake, and Gausemeier 2012; *Design methodology for intelligent technical systems 2014*).

4.4 The context of adaptive systems

Changeable systems can be modified after their implementation. Ross, Rhodes, and Hastings (2008) define the changeability as a possible transformation of a system to a new condition within a period of time. They identify the agent as impulse, the change mechanism and the effect of the change as its three constituents. According to Ross, Rhodes, and Hastings (2008), a system is flexible in case of an external agent and adaptable in case of an internal agent. Flexibility and reconfigurability are subthemes of changeable systems. Ferguson et al. (2008) formulate the demand for such systems as a consequence of the requirements: to be able to fulfil different tasks over a period of time, to be able to be transferred into new configurations and to remain operational despite the failure of individual system components. They define the flexibility of a system as the simplicity of its possible change. According to Olewnik et al. (2004), flexible systems perform real-time adaptations. Their performance is enhanced by their adaptability in predictable environments and they are robust due to unpredictable influences. Adaptive systems are a precursor to intelligent technical systems. Due to applied algorithms, they are able to adapt to changing conditions without user input (Feigh, Dorneich, and Hayes 2012). The limit of such systems lies in the adaptability to requirements of an unpredictable environment (*Design methodology for intelligent technical systems 2014*).

4.5 The context of embedded systems

Mechatronic systems with integrated microcomputers are defined as embedded systems. Today about 80% of existing computers are installed in components or products. In most cases, micro-controllers are used as the preferred hardware. Unlike multi-purpose computers, they follow a predefined programme which may be stored on the controller itself. Micro-controllers are differentiated by their computing power. Due to their low-cost availability, 8-bit controllers are often installed, even if their computing power is not very high. For computationally intensive tasks, there are 16-bit or 32-bit micro-controllers. In mechatronic systems, micro-controllers are used for the interaction with the sensors and actuators. Embedded systems are a technical basis for CPS. The implementation of information technology enables intelligent control of individual components, but also their decentralized interlinking towards a networked system (Wolf 2012; Czichos 2015).

4.6 Definition of intelligent technical systems

Intelligent technical systems are, in addition to the implementation of intelligent products, a partial aspect of the fourth industrial revolution (industry 4.0). In accordance with the implementation strategy by the platform industry 4.0, objectives are increased production efficiency, higher flexibility, implementation of downstream services and the physical and cognitive support of employees (BITKOM, VDMA, and ZVEI 2015). Intelligent products carry the knowledge of their manufacturing process in themselves and independently find their way through a configurable production chain (Brettel et al. 2014). The leading-edge cluster Intelligent Technical Systems (2012) OstWestfalen-Lippe (it's OWL) introduces the concept of the intelligent technical system. It is based on the combination of different knowledge domains such as information technology, cognitive science or neurobiology. It is a further development of mechatronic systems with regard to its information processing (Dumitrescu, Jürgenhake, and Gausemeier 2012). Cognitive data processing enables the adaptability of the system behaviour and supplements previously rigid controls. Intelligent technical systems are capable of learning and can react flexibly and intelligently to changing requirements and conditions. The learning ability is based on processed information and takes place, according to Dumitrescu, Jürgenhake, and Gausemeier (2012), on the three levels of cognitive, associative and non-cognitive control. Another aspect of intelligent technical systems is their close networking. This is ensured by means of a communication system which allows the exchange of information between intelligent technical systems and their subsystems. The interaction with humans is a significant aspect, manufactured via a human machine interface. The basis for the implementation of intelligent technical systems is created by technological developments such as smaller electronics, the development of new software and methods for handling complexity and the possible virtual networking of information systems. In this context, cyclic-physical systems represent the interlinking of physical systems with the virtual world (Gausemeier et al. 2013; *From machine-to-machine to the Internet of things 2014*; "Intelligent Technical Systems OstWestfalenLippe - Proceedings of 1st Joint International Symposium on System-integrated Intelligence: New Challenges for Product and Production Engineering - Roman Dumitrescu, Christoph Jürgenhake, Jürgen Gausemeier - Publikationen Heinz Nixdorf Institut").

4.7 Cyber-physical systems

Various terms such as Intelligent Technical Systems, 'Industry 4.0', 'Internet of everything', 'Internet of Things', 'FOG', 'System of Systems' or 'machine-to-machine' describe today's issue of a close combination of the virtual and physical environment. In this context, the general term CPS has prevailed. The prefix 'cyber' refers to cybernetics as previously described. The association with the cyberspace often leads to misunderstandings. Wireless networking can be an aspect of CPS, but is not a requirement. The term was founded in 2006 in the National Science Foundation in the United States. This refers to the convergence of computer-based components and physical components (plants) in one system. It involves the close interaction between both levels (Lee and Seshia 2015).

Today, the technological requirements for such systems are provided by miniaturized electronics, the development of high-performance software and the possible networking of information systems. Software is an important aspect of CPS. They are also known as 'software-intensive systems'. Wang, Torngren, and Onori (2015) assume that the software is a major factor of the investment costs for the implementation of CPS. The potential of the software stems from its high flexibility. Any hardware can fulfil various tasks based on different software, which is not material bound, nor subject to technical restrictions. Software can be easily copied and offers great design freedom. Based on the software, various aspects such as computing, communications or the evaluation of information can be negotiated within a system. In practice, the high flexibility of the software requires a strict limitation towards the system's actual needs (*Cyber-Physical Systems 2010*).

In many sectors such as transport, the manufacturing industry, the building industry or aviation, CPS are currently being researched and applied. Following Wang, Torngren, and Onori (2015), there is a corresponding number of approaches towards a definition. These are either specific and relate to a concrete field of application, or they are too broad for an applicable delimitation of CPS. CPS are, for example, defined as a transferable technology for monitoring networked systems on their computer-based and physical level. Researchers have moved towards the formulation of CPS characteristics for a common comprehension across different platforms. Wang, Torngren, and Onori (2015) identify 10 characteristics of a CPS. These include whether it is an embedded or IT-dominated system, whether it is a single application or cross-platform application, and whether the system is open or closed. Furthermore, it denotes the degree and type of automation, the adaptability of the system and the degree of integration as aspects to consider. Following Wang, Torngren, and Onori (2015), a CPS can also be characterized by the degree of decentralization of its control, as well as by whether there is a human–computer interaction, or if it is completely autonomous. As a final aspect, Wang, Torngren, and Onori (2015) list the degree of vertical and horizontal integration of the system.

Broy characterizes CPS by a direct linking between the physical and the digital environment. From his point of view, the multi-functionality, ensured by functional integration, is as crucial as the exchange of the systems with each other and with their environment. Here, Broy talks about an extensive interaction within and across networks. Moreover, autonomy and adaptability play a role against the background of changing and dynamic operating environments. Following Broy, long-term operations, the functional and access security and the reliability of the systems are additional characteristics. Broy classifies systems according to their degree of crosslinking. He distinguishes five levels, starting with a local, non-crosslinked and mono-functional system. This is followed by multi-functional but non-networked systems, by loosely networked systems and also by networks of functional systems. On top there are systems of systems, such as CPS (*Cyber-Physical Systems 2010*).

In the context of high expectations towards CPS, Monostori (2014) recognizes future challenges in research and development. These include the adaptability and autonomy of the systems, the development of advanced algorithms for the systems cooperation and foresight in continuously changing environments. Moreover, Monostori (2014) identifies the merge of physical systems and virtual systems but also the human–machine interaction as future challenges.

4.8 Alternative designations

Starting from the term 'intelligent technical systems', further designations are identified that describe the subject field. Many of the terms are composed of an attribute and an application. Names identified as being independent are listed under the category stand-alone terms (Table 6).

4.9 Criteria of intelligent technical systems

Against the background of the extensive and complex subject of intelligent technical systems in the industry, the following lists of criteria are identified as an addition to the definitions found.

Dumitrescu, Jürgenhake, and Gausemeier (2012) describe the characteristics of intelligent technical systems organized into the four categories: adaptability, anticipation, user-friendliness and robustness. They also identify capabilities to which they can be moored (Table 7).

The following characteristics by Dumitrescu, Jürgenhake, and Gausemeier (2012) refer to the intelligence itself. Some of the aspects, such as the adaptability, interfere with the previous listing. The criteria relate in particular to control capabilities, such as the exchange of information or the ability to learn (Table 8).

Table 9 presents a concept map for CPS ('Cyber-Physical Systems - a Concept Map').

Table 6. Alternative designations in relation to intelligent technical systems.

Property	Application	Stand-alone term
Intelligent	System	Cybernetics
Smart	Technical System	Technical cybernetics
Cyber-physical	Environment	Internet of Things
Embedded	Machine	Industry 4.0
Cognitive		Things that think
Adaptive		Systems of systems
Self-Adaptive		Internet of everything
Cybernetic		
Mechatronic		
Self-Optimizing		
Adaptronic		
Expert		

Table 7. Criteria of intelligence technical systems by Dumitrescu, Jürgenhake, and Gausemeier (2012).

Adaptive	Robust	Anticipative	User friendly
Environmental interaction	Flexible	Processing empirical knowledge	Interact sensitively with user
Autonomous	Unpredictable environments	Anticipate future impacts	Adapt to user
Evolve-ability within framework	Overcome Uncertainties	Anticipate possible states	Comprehensible behaviour
Ensure long-term existence	Overcome lack of information		

Table 8. Criteria of intelligence by Dumitrescu, Jürgenhake, and Gausemeier (2012).

Active	Embedded	Exchange information	
Flexible	Adaptive	Action-control	Information representation
Learning ability	Anticipative		

Lee, Bagheri, and Kao (2015) define a '5C architecture', in line with the automation pyramid, as a framework for the implementation of CPS in the industry. They divide the structure of CPS into five levels. The Connection level corresponds to the field level and comprises the connection to the sensor network. On the Conversion level, data are processed into information. On the Cyber level, the exchange with other systems takes place. The Cognition level includes decision support and the monitoring of the system, while the Configuration level includes the 'Resilient control system' (Lee, Bagheri, and Kao 2015) (Table 10).

In consideration of all constellations, the criteria relate primarily to the, for example, networked or distributed compilation of intelligent technical systems, as well as to the abilities of their control, for example, to be able to act in unpredictable environments.

5. Discussion and further research

The investigation into the two subject areas provides an independent overview of the understanding and development of a respective intelligent system. In the industry, the application of CPS to production processes leads to a new development stage that has not yet been achieved in the field of adaptive building envelopes. Insights and strategies from the industry can be transferred to the building envelope for an increase in performance of the systems. This refers to the manufacturing processes of a façade industry equipped with intelligent technical systems. Menges (2015) describes such a possible application scenario of CPS in architecture-related manufacturing processes. It is assumed that in addition to an increase in productivity and flexibility, there is a potential in the individualization of façade production, the so-called mass customization (Brettel et al. 2014). On the other hand, an application to the functioning of intelligent façades in building operation is conceivable. Against the background of an increasing automation of the building envelope, a potential is seen in the networking and intelligent control of façade components. It is expected that the

Table 9. Cyber-physical systems concept map.

Feedback systems	Cyber security	Design tools and methodology	
Networked	Resilience	Specification	Hybrid Models
Distributed	Privacy	Modelling	Heterogeneous Models
Adaptive	Malicious Attacks	Analysis	Networking
Predictive	Intrusion Detection		Interoperability
Intelligent			Time synchronization
Real time		Scalability	Modularity
Human interaction		Complexity Management	Synthesis
			Interfacing
		Validation	Assurance
		Verification	Certification
			Simulation
			Stochastic Models

Table 10. '5C architecture' for cyber-physical systems.

Level	Attributes		
Configuration	Self-configure resilience	Self-adjust variation	Self-optimize disturbance
Cognition	Simulation and synthesis	Remote visualization	Collaborative decisions
Cyber	Twin model	Variation identification	Clustering
Conversion	Smart analytics machine health	Smart analytics data correlation	Degradation/Performance prediction
Connection	Plug & Play	Tether-free communication	Sensor network

application of CPS can contribute to the future viability of multi-functional adaptive façades. The transferability of strategies must be examined in subsequent research for the specific cases.

6. Conclusion

Given the found and not uniformly defined terms, it becomes clear that there is an active and unfinished discussion about intelligent systems. The study also shows that there is no complete and general understanding of a system's intelligence in façade engineering and in the industry. The following conclusions are drawn on the specific sub-questions:

Contrary to the expectation that the intelligence of the building envelope refers to its intelligent control, the concept is mainly related to its construction-related adaptability. This recognition is supported in the lists of criteria of an intelligent façade, in which primarily automated components are named instead of capabilities of their control. In the industry, a distinction is made between flexible and adaptive systems with regard to an external or internal agent. This separation has not yet been clearly defined with regard to the façade. The distinction between the term 'adaptable' for constructively adaptable façades and 'adaptive' for those façades that adapt independently on the basis of automation technologies appears necessary. Aspects like artificial intelligence and self-organization were identified in the subject field. In the found definitions, they appear as a sub-range of respective specifications. No specific designation has been found for such façade systems, which can be regarded as intelligent because of intelligent control, for example in the form of a decision process or the mapping of learning behaviours. Such properties have been identified in the industry as crucial to the intelligence of a technical system. In its history of developments, new terms addressed technological improvements of the façade. The term skin represents adaptive features and the ability of self-regulation. A descriptive supplement is missing, which emphasizes cognitive abilities. Such a façade must be able to make decisions on the basis of collected information and in the awareness of existing requirements. Against this background, the concept of a thinking façade would be appropriate.

The study identifies the performance as the main objective and the multi-functionality of the façade as a relevant aspect. Furthermore, the diversity of existing and non-uniform designations is to be noted.

The investigation determines different constellations of characteristics of the intelligent façade. It is crucial how the concept of intelligent façade is interpreted. There are constellations which deal explicitly with characteristics of the ability to adapt. Furthermore, there are lists of the components that are available with regard to an adaptive system, as sensors and actuators. The foundations are hardly comparable against the background of different conceptions of an intelligent façade. No characterization has been found which specially focuses on the control strategy and the behaviour such as learning ability or self-organization.

The concept of intelligent technical system reflects the specific application field of intelligent production in the global context CPS. It is characterized by the development of industry 4.0 in the German economy. The study could not determine a general definition of an intelligent technical system; instead, it provides a description of the development and characterization of the properties and capabilities of such a system. The study shows that the transformation from mechatronic systems to intelligent systems is based on the combination of many fields of knowledge. The use of cognitive controls and the interactive networking between machines with each other and with humans are highlighted as important aspects.

The implementation of intelligent technical systems is based on multiple technological requirements. Against this background, control principles of mechatronic and adaptive systems and the embedding of computer technology into components are identified as important aspects. Cybernetics is recognized as a relevant science because it provides a conceptual framework model for the interaction of machines and people in such a digitized production environment.

The study identifies criteria both in the direct context of intelligent technical systems and in the expanded understanding of CPS. In addition to a mindmap-based set-up, the deployment as an advanced automation pyramid appears as promising to identify capabilities of controlling an intelligent system.

Acknowledgement

The study is part of a PhD research project, and is not subject to any specific funding.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes on contributors

Jens Böke is a PhD candidate in the department Architectural Engineering and Technology at the Delft University of Technology. His research focuses on intelligent building envelopes. He is a research assistant at the Faculty of Architecture at the Cologne University of Applied Sciences, where he also heads the CAM Laboratory.

Professor Dr. Ing. *Ulrich Knaack* (1964) was trained as an architect at the RWTH Aachen / Germany. After earning his degree, he worked at the university as researcher in the field of structural use of glass and completed his studies with a PhD. In his professional career, Knaack worked as architect and general planner in Düsseldorf/ Germany, succeeding in national and international competitions. His projects include high-rise and offices buildings, commercial buildings and stadiums. In his academic career, Knaack was professor for Design and Construction at the Hochschule OWL / Germany. He also was and still is appointed professor for Design of Construction at the Delft University of Technology / Faculty of Architecture, Netherlands where he developed the Façade Research Group. In parallel, he is professor for Façade Technology at the TU Darmstadt / Faculty of Civil engineering/ Germany where he participates in the Institute of Structural Mechanics + Design. He organizes interdisciplinary design workshops and symposiums in the field of facades and is author of several well-known reference books, articles and lectures.

Marco Hemmerling is Professor of Computational Design in Architecture at the Cologne University of Applied Sciences and Visiting Professor at the Politecnico di Milano, School of Architecture and Urban Planning. Previously he was Professor at the Detmold School of Architecture and Interior Design and Director of the post-graduate Master program Computational Design and Construction at the East-Westphalia University of Applied Sciences. He is a coopted member of the Association of German Architects and the German Association of Craftsmen.

References

4dsocial. 2007. “Interactive Design Environments.” In *Architectural Design Profile*, edited by Lucy Bullivant, 54–61. Chichester: Wiley-Acad.

Addington, Michelle. 2009. “Contingent Behaviours.” *Architectural Design* 79: 12–17. doi:10.1002/ad.882.

Aelenei, Daniel, Laura Aelenei, and Catarina Pacheco Vieira. 2016. “Adaptive Façade: Concept, Applications, Research Questions.” *Proceedings of the 4th International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2015)* 91: 269–275. doi:10.1016/j.egypro.2016.06.218.

Aelenei, Laura, Marcin Brzezicki, Ulrich Knaack, Andreas Luible, Marco Perino, and Frank Wellershoff. 2015. “COST Action TU1403 - Adaptive Facades Network.” In *Adaptive facade network — Europe* , edited by Andreas Luible, Mauro Overend, Laura Aelenei, Ulrich Knaack, Marco Perino, and Frank Wellershoff. Delft: TU Delft Open.

Al horr, Yousef, Mohammed Arif, Martha Katafygiotou, Ahmed Mazroei, Amit Kaushik, and Esam Elsarrag. 2016. “Impact of Indoor Environmental Quality on Occupant Well-Being and Comfort: A Review of the Literature.” *International Journal of Sustainable Built Environment* 5: 1–11. doi:10.1016/j.ijsbe.2016.03.006.

Anshuman, Sachin. 2005. Responsiveness and Social Expression; Seeking Human Embodiment in Intelligent Façades, Smart Architecture: Integration of Digital and Building Technologies, Association for Computer Aided Design in Architecture (ACADIA), Savannah, GA, 13–16.

Bakker, L. G., E. C. M. Hoes-van Oeffelen, R. C. G. M. Loonen, and J. L. M. Hensen. 2014. "User Satisfaction and Interaction with Automated Dynamic Facades: A Pilot Study." *Building and Environment* 78: 44–52. doi:10.1016/j.buildenv.2014.04.007.

BITKOM, VDMA, and ZVEI. 2015. "Umsetzungsstrategie Industrie 4.0." Berlin, Frankfurt am Main.

Brettel, Malte, Niklas Friederichsen, Michael Keller, and Marius Rosenberg. 2014. 'How Virtualization, Decentralization and Network Building Change the Manufacturing Landscape: An Industry 4.0 Perspective'. World Academy of Science, Engineering and Technology, International Science Index 85, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, 8(1), 37 - 44.

Capeluto, Guedi, and Carlos Ernesto Ochoa. 2017. "What Is a Real Intelligent Envelope?" In *Intelligent Envelopes for High-Performance Buildings*, 1–20. Cham: Springer International doi:10.1007/978-3-319-39255-4.

Clements-Croome, T. D. J. 1997. "What Do We Mean by Intelligent Buildings?" *Automation in Construction* 6: 395–400.

Compagno, Andrea. 1999. *Intelligente Glasfassaden: Material, Anwendung, Gestaltung=Intelligent Glass Façades: Material, Practice, Design*. 4th, rev. and enlarged ed. Basel: Birkhäuser-Verlag.

Cyber-Physical Systems. 2010. *Innovation durch softwareintensive eingebettete Systeme ; [acatech Symposium …]. 2010. Acatech DISKUTIERT*. Berlin: Springer.

"Cyber-Physical Systems - a Concept Map." www.cyberphysicalsystems.org.

Czichos, Horst. 2015. *Mechatronik: Grundlagen und Anwendungen technischer Systeme. 3., überarb. u. erw. Aufl. 2015 ed, Lehrbuch*. Wiesbaden: Springer Fachmedien Wiesbaden GmbH.

Del Grosso, A. E., and P. Basso. 2010. "Adaptive Building Skin Structures." *Smart Materials and Structures* 19, doi:10.1088/0964-1726/19/12/124011.

Design Methodology for Intelligent Technical Systems. 2014. *Develop Intelligent Technical Systems of the Future. Lecture Notes in Mechanical Engineering*. Heidelberg: Springer.

Douglas, James. 1996. "Building Performance and its Relevance to Facilities Management." *Facilities* 14: 23–32. doi:10.1108/02632779610112508.

Drossel, W.-G., H. Kunze, A. Bucht, L. Weisheit, and K. Pagel. 2015. "Smart3 – Smart Materials for Smart Applications." *Procedia CIRP* 36: 211–216. doi:10.1016/j.procir.2015.01.055.

Dumitrescu, Roman, Christoph Jürgenhake, and Jürgen Gausemeier. 2012. Intelligent Technical Systems OstWestfalenLippe. In Proceedings of the 1st Joint International Symposium on System-integrated Intelligence, Hannover, Germany, 27–29 June 2012. ISSN:0944-6524

Favoino, Fabio, Qian Jin, and Mauro Overend. 2014. "Towards an Ideal Adaptive Glazed Façade for Office Buildings." *6th International Conference on Sustainability in Energy and Buildings, SEB-14* 62: 289–298. doi:10.1016/j.egypro.2014.12.390.

Feigh, K. M., M. C. Dorneich, and C. C. Hayes. 2012. "Toward a Characterization of Adaptive Systems." *Human Factors: The Journal of the Human Factors and Ergonomics Society* 54: 1008–1024. doi:10.1177/0018720812443983.

Ferguson, S., K. Lewis, A. Siddiqi, and O. L. De Weck. 2008. "Flexible and Reconfigurable Systems: Nomenclature and Review." Paper presented at the 2007 Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC2007, 2008.

Fortmeyer, Russell Martin, and Charles D. Linn. 2014. *Kinetic Architecture: Designs for Active Envelopes*. Mulgrave, Victoria: Images Publishing Group.

Frazer, J. H. 1993. "The Architectural Relevance of Cybernetics." *Systems Research* 10: 43–48. doi:10.1002/sres.3850100307.

From machine-to-machine to the Internet of things. 2014. *Introduction to a new age of intelligence*. Amsterdam: Elsevier Academic Press.

Gausemeier, Jürgen, Harald Anacker, Anja Maria Czaja, Helene Wassmann, and Roman Dumitrescu. 2013. Auf dem Weg zu intelligenten technischen Systemen, April 2013.

Hartkopf, Volker, and Vivian Loftness. 1999. "Global Relevance of Total Building Performance." *Automation in Construction* 8 (4): 377–393. doi:10.1016/S0926-5805(98)00085-5.

Hausladen, Gerhard, Michael de Saldanha, and Petra Liedl. 2008. *Climateskin: Concepts for Building Skins That can do More with Less Energy*. Basel: Birkhäuser.

Hausladen, Gerhard, Michael de Saldanha, Petra Liedl, and Christina Sager. 2005. *Climate Design: Solutions for Buildings That can do More with Less Technology*. Basel: Birkhäuser.

Herzog, Thomas, Roland Krippner, and Werner Lang. 2004. *Facade Construction Manual*. Basel: Birkhauser-Publishers for Architecture.

Heylighen, Francis, and Cliff Joslyn. 2001. "Cybernetics and Second Order Cybernetics." *Encyclopedia of Physical Science & Technology* 4: 155–170.

Intelligent Technical Systems OstWestfalenLippe. 2012. "Intelligent Technical Systems OstWestfalenLippe". Proceedings of 1st Joint International Symposium on System-integrated Intelligence: New Challenges for

Product and Production Engineering - Roman Dumitrescu, Christoph Jürgenhake, Jürgen Gausemeier - Publikationen Heinz Nixdorf Institut.
Interactive architecture. 2016. “Adaptive World.” In *Architecture Briefs*. 1st ed., edited by Michael Fox, 7–13. New York: Princeton Architectural Press.
Jencks, Charles. 2015. “Nonlinear Architecture (1997).” In *The Digital Turn in Architecture 1992–2012*, edited by Mario Carpo, 80–107. Hoboken, NJ: John Wiley & Sons, Inc.
Kagermann, H., W. Wahlster, and J. Helbig. 2013. “Recommendations for implementing the strategic initiative INDUSTRIE 4.0.” In.: Acatech – National Academy of Science and Engineering.
Klein, T. 2013. “Integral Facade Construction: Towards a New Product Architecture for Curtain Walls.” doi:10.4233/uuid:f90c1c7e-b6b3-42de-8f17-22cc23981de7.
Knaack, Ulrich, Tillmann Klein, Marcel Bilow, and Thomas Auer. 2014. *Façades: Principles of Construction*. Second and revised edition ed.Basel: Birkhäuser.
Kroner, Walter M. 1997. “An Intelligent and Responsive Architecture.” *Automation in Construction* 6 (5–6): 381–393. doi:10.1016/S0926-5805(97)00017-4.
Lee, Jay, Behrad Bagheri, and Hung-An Kao. 2015. “A Cyber-Physical Systems Architecture for Industry 4.0-Based Manufacturing Systems.” *Manufacturing Letters* 3: 18–23. doi:10.1016/j.mfglet.2014.12.001.
Lee, Edward Ashford, and Sanjit Arunkumar Seshia. 2015. *Introduction to Embedded Systems - A Cyber Physical Systems Approach*. 2nd ed. lulu.com.
Loonen, R. C. G. M., F. Favoino, J. L. M. Hensen, and M. Overend. 2017. “Review of Current Status, Requirements and Opportunities for Building Performance Simulation of Adaptive Facades.” *Journal of Building Performance Simulation* 10: 205–223. doi:10.1080/19401493.2016.1152303.
Loonen, R. C. G. M., Roel J. M. Rico-Martinez, F. Favoino, M. Brzezicki, C. Menezo, G. La Ferla, and L. Aelenei. 2015. *Design for Façade Adaptability -Towards a Unified and Systematic Characterization*, 1274–1284. Bern: springer.
Loonen, R. C. G. M., M. Trčka, D. Cóstola, and J. L. M. Hensen. 2013. “Climate Adaptive Building Shells: State-of-the-art and Future Challenges.” *Renewable and Sustainable Energy Reviews* 25: 483–493. doi:10.1016/j.rser.2013.04.016.
Macias-Escriva, Frank D., Rodolfo Haber, Raul del Toro, and Vicente Hernandez. 2013. “Self-adaptive Systems: A Survey of Current Approaches, Research Challenges and Applications.” *Expert Systems with Applications* 40: 7267–7279. doi:10.1016/j.eswa.2013.07.033.
Meagher, Mark. 2015. “Designing for Change: The Poetic Potential of Responsive Architecture.” *Frontiers of Architectural Research* 4: 159–165. doi:10.1016/j.foar.2015.03.002.
Menges, Achim. 2015. “The New Cyber-Physical Making in Architecture: Computational Construction.” *Architectural Design* 85: 28–33. doi:10.1002/ad.1950.
Moloney, Jules. 2011. *Designing Kinetics for Architectural Facades: State Change*. Abingdon: Routledge.
Monostori, László. 2014. “Cyber-physical Production Systems: Roots, Expectations and R&D Challenges.” *Procedia CIRP* 17: 9–13. doi:10.1016/j.procir.2014.03.115.
mppf - The multifunctional plug&play approach in facade technology. 2015. Graz: Verl. der Technischen Univ. Graz.
Ochoa, C. E., and I. G. Capeluto. 2008. “Strategic Decision-Making for Intelligent Buildings: Comparative Impact of Passive Design Strategies and Active Features in a Hot Climate.” *Building and Environment* 43: 1829–1839. doi:10.1016/j.buildenv.2007.10.018.
Oesterreich, Thuy Duong, and Frank Teuteberg. 2016. “Understanding the Implications of Digitisation and Automation in the Context of Industry 4.0: A Triangulation Approach and Elements of a Research Agenda for the Construction Industry.” *Computers in Industry* 83: 121–139. doi:10.1016/j.compind.2016.09.006.
Olewnik, Andrew, Trevor Brauen, Scott Ferguson, and Kemper Lewis. 2004. “A Framework for Flexible Systems and Its Implementation in Multiattribute Decision Making.” *Journal of Mechanical Design* 126: 412. doi:10.1115/1.1701874.
Park, Cheol-Soo, Godfried Augenbroe, Nader Sadegh, Mate Thitisawat, and Tahar Messadi. 2004. “Real-Time Optimization of a Double-Skin Façade Based on Lumped Modeling and Occupant Preference.” *Building Simulation for Better Building Design* 39: 939–948. doi:10.1016/j.buildenv.2004.01.018.
Pickering, Andrew. 2015. “Cybernetics A2 - Wright, James D.” In *International Encyclopedia of the Social & Behavioral Sciences*, 645–650. Oxford: Elsevier doi:10.1016/B978-0-08-097086-8.85005-9.
Ross, A. M., D. H. Rhodes, and D. E. Hastings. 2008. “Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining System Lifecycle Value.” *Systems Engineering* 11: 246–262. doi:10.1002/sys.20098.
Sala, Marco. 1994. “The Intelligent Envelope: The Current State of the art.” *Renewable Energy* 5 (5–8): 1039–1046. doi:10.1016/0960-1481(94)90131-7.
Schumacher, Michael, Oliver Schaeffer, and Michael-Marcus Vogt. 2009. *Move: Dynamic Components and Elements in Architecture*. Basel: Springer [distributor].
Sher, Elite, Angelos Chronis, and Ruairi Glynn. 2014. “Adaptive Behavior of Structural Systems in Unpredictable Changing Environments by Using Self-Learning Algorithms: A Case Study.” *Simulation* 90: 991–1006. doi:10.1177/0037549714543090.
Sobek, Werner, and Patrick Teuffel. 2001. “Adaptive Systems in Architecture and Structural Engineering”, July 30.

Von Foerster, Heinz. 2003. "Cybernetics of Cybernetics." In *Understanding Understanding*, 283–286. New York: Springer.

Wang, Lihui, Martin Torngren, and Mauro Onori. 2015. "Current Status and Advancement of Cyber-Physical Systems in Manufacturing." *Journal of Manufacturing Systems* 37: 517–527. doi:10.1016/j.jmsy.2015.04.008.

Weyer, Stephan, Mathias Schmitt, Moritz Ohmer, and Dominic Gorecky. 2015. "Towards Industry 4.0 - Standardization as the Crucial Challenge for Highly Modular, Multi-Vendor Production Systems." *15th IFAC Symposium On Information Control Problems In Manufacturing INCOM 2015* 48: 579–584. doi:10.1016/j.ifacol.2015.06.143.

Wiener, Norbert. 2013. *Cybernetics or Control and Communication in the Animal and the Machine*. 2nd ed.Cambridge, MA: MIT Press.

Wigginton, M., and J. Harris. 2002. "Intelligent Skins." Butterworth-Heinemann.

Wolf, Marilyn. 2012. "Embedded Computing." In *Computers as Components: Principles of Embedded Computing System Design*, 1–50. Waltham: Elsevier.

Wong, J. K. W., H. Li, and S. W. Wang. 2005. "Intelligent Building Research: A Review." *Automation in Construction* 14: 143–159. doi:10.1016/j.autcon.2004.06.001.

Yang, J., and H. Peng. 2001. "Decision Support to the Application of Intelligent Building Technologies." *Renewable Energy* 22 (1–3): 67–77. doi:10.1016/S0960-1481(00)00085-9.

Yiannoudes, Socrates. 2016. *Architecture and Adaptation: From Cybernetics to Tangible Computing*. New York: Routledge, Taylor & Francis Group.