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DISSERTATION

System Mapping and Generative Hierarchical Zone Control Structure for a Scalable Building Control Logic

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KURZFASSUNG

Die Bedeutung von Gebäudemanagement für die Reduktion von Energieverbrauch führt dazu, dass die Bauindustrie vermehrt neueste verfügbare Technologien für hochgradig integrierte Systeme in Gebäudeautomation und -regelung einsetzt.
Eine optimierte Planung und der Betrieb von Gebäuden verlangt die Auslegung von Gebäuderegelungssystemen, die über die Steuerung von abgegrenzten Teilsystemen hinausgeht. Ganzheitliche Konzepte der Gebäuderegelung ermöglichen es Optimierungspotentiale auszunützen, die gerade in den Verbindungen der hochgradig verknüpften physikalischen Teilsystemen zu finden sind.

Entwicklungsprozesse mit komplexen Gebäudesystemen setzen einen hohen Kooperationsgrad der beteiligten Ingenieursbereiche voraus und erfordern übergreifendes Verständnis und effiziente Kommunikation.

Das Ziel dieser Dissertation ist es eine Methode zu entwickeln, um für die Planung der Gebäudeautomation regelungsbezogene und disziplinübergreifende Entwicklungs- und Arbeitsprozesse zu unterstützen und die Abstimmung zwischen den Gewerken zu verbessern.

Dazu wird eine automatisierbare Methodik für die Systemdarstellung eines Gebäudes und ein darauf aufbauender Generierungsprozess für eine mehrstufig-hierarchischen Regelungsstruktur präsentiert.

Die Arbeit folgt dabei einem strukturellen Systemansatz und einer Herangehensweise im Sinne der klassischen Regelungstheorie.

Für die Aufteilung des komplexen Gesamtsystems in kleinere Einheiten wird ein modulares Zonen-Konzept zur Abbildung der gekoppelten physikalischen Teilsysteme eines Gebäudes vorgestellt. Die Teilsysteme werden in einfache Regelungskreise eingebunden und zu Mehrgrößensystemen verknüpft. Diese werden dann in einem mehrstufigen Prozess weiter zu einer Regelstruktur in mehreren hierarchischen Ebenen bzw. Regelkreisen mit unterschiedlichen Koordinationsfunktionen aufgebaut. Besonderer Schwerpunkt liegt dabei auf einer automatisierbaren Umsetzung und auf der Skalierbarkeit des Prozesses.

Das resultierende Regelungsmodell mit der Darstellung der Systemstruktur und der Regelungshierarchie deckt sowohl die physikalischen Systeme im Gebäude, die Korrelationen des Systemverhaltens als auch das Konzeptmodell der Gebäuderegelung ab.
Von besonderer Bedeutung ist ein solches Regelungsmodell im Zusammenhang mit hochentwickelten Regelalgorithmen wie Mehrgrößenregelung, hierarchischer Regelung und modellbasierter Regelungen.

Der vorgestellte strukturelle Ansatz nutzt die Datenstruktur von BIM bzw. der IFC Datenmodelle und ermöglicht eine einfache Integration in Architektur- und Simulations-Arbeitsabläufe. Mit seinem interdisziplinären Ansatz stellt das Konzept verschiedene Systemdarstellungen zur Verfügung, um die Anforderungen der beteiligten Ingenieursbereiche abzudecken.

ABSTRACT

With the rapid development of building technology and the importance of building control in the context of reduction of energy consumption, the Architecture, Engineering and Construction industry (AEC) is directed towards highly integrated building automation and management systems.

To optimize building operations, the design of control systems has to go beyond optimizing the building operation on the level of delimited subsystems or equipment. A holistic system approach of building control allows to exploit optimization potentials within the highly interrelated physical building system.

Dealing with complex building systems requires a high degree of cooperation among the participating engineering domains. Development processes call for efficient communication and multidisciplinary collaboration models. This thesis intends to support such control related inter- and transdisciplinary work processes.

The work develops a method to support control-related and multidisciplinary development processes for the planning of building control systems and to improve the coordination between involved engineering domains.
To this, an automatable procedure for a system decomposition and mapping of a building's systems and a consecutive generation process for a multi-level hierarchical control structure is presented.

The thesis follows a structural systems approach and adheres to the classical closed-loop control theory.

A modular zone concept is developed for the decomposition and structural mapping of the complex building system into simpler subsystems; the concept also serves for the presentation of the highly interrelated physical effects between these subsystems. These subsystems are combined to single-parameter control circuits and further aggregated to multi-parameter systems.
In an automated process a hierarchical multi-level control scheme with defined coordination tasks is generated. Emphasis is on an automated implementation and on the scalability of the entire process.

The resulting control model represents the system structure and the control hierarchy; it is covering the physical systems in the building, the interacting system characteristics as well as the conceptual model of the building control. This is of special interest when advanced building control strategies as multi-parameter control, hierarchical control and model-based controls are discussed.

The structural approach links to the structure of BIM, respectively to its IFC data models and allows integration into architectural and simulation workflows. The interdisciplinary approach provides multidisciplinary system views to meet the requirements of the participating engineering domains.

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CONTENTS

1 Introduction

With the rapid development of building technology and the importance of building control for the reduction of energy consumption, the Architecture, Engineering and Construction industry (AEC industry) is geared towards highly integrated building automation and management systems. Building automation and control systems target economic objectives as cost- and energy efficiency (Mahdavi 2003): They provide for optimal working or living environment and sustain productivity, comfort and occupants' health. Latest developments in advanced building control systems and the vast variety of available products entail an increasing complexity of building systems and their structure.

To optimize building operations, the design of control systems has to go beyond optimizing the building operation on the level of delimited subsystems or equipment. The increased capability of electronics in control and network systems provides means to take a holistic system approach towards building control and to exploit the optimization potentials lying in the interfaces of the highly interrelated physical building system.

At the same time, building systems design is confronted with increasing complexity of building systems and communications- and organizational challenges among the involved engineering domains. For the multidisciplinary field of control engineering and its jointly involved engineering domains a systematic and transferrable representation of the buildings' systems, their relations, dependencies and control structure is essential. Highly complex systems and requirements for cross-domain teamwork have demonstrated the need for tools enhancing the inter-/transdisciplinary workflows.

In a structural approach, this thesis aims to support such control related inter- and transdisciplinary work processes. A prototypical tool maps the physical building systems, their relations and interactions. An automated method is implemented to generate a hierarchical multi-level control structure. It provides multidisciplinary system views to meet the requirements of the participating engineering domains and to facilitate the cooperative efforts.

A structural system model of a building, with its physical systems and feedback control systems is of special importance when advanced building control strategies as multi-parameter control, hierarchical control and model-based controls are discussed.

Yet, there are only few structural approaches towards a general scheme, aligning impacts and effects with building physics, -systems, -control structure and control components.

1.1 Previous and related work

Previous work

This thesis refers to previous work on a structural control system approach, focusing on a rule-based generation of a closed-loop hierarchical control structure for building control systems (Mahdavi and Rader 2014, Rader and Mahdavi 2015, Mertz and Mahdavi 2003). Their approach builds on an elementary, yet comprehensible system representation of a building's physical and control subsystem. The system mapping is based on a simple arrangement of device elements (imposed action), and sensing elements (system reaction) within architectural entities.

A performed survey study found the presented method to be useful towards understanding the impacts and improvement of buildings energy performance. It was regarded as a support for the configuration of building's technical systems and facilitates inter-domain communication (Rader and Mahdavi 2015, Mertz and Mahdavi 2003).

The underlying manual process requires users with experience, especially with the multitude of cause-effect relationships (Mahdavi and Rader 2014) in the form of primary-, secondary effects and effects related to mutually influencing zones.

That approach builds on an noncomplex, yet comprehensible system representation of a building's control subsystem. A survey study found the approach to be effective in supporting the configuration of buildings technical systems, to facilitate inter-domain communication and to be useful towards understanding and supporting improvement of buildings energy performance (Rader and Mahdavi 2015, Mertz and Mahdavi 2003).

Schemes involving a large number of zones and mutually influencing devices are getting very complex (Rader and Mahdavi 2015, Mahdavi and Rader 2014).
The presented approach, however, showed some shortcomings in context with the scalability to more complex building structures and systems; schemes involving a large number of zones and mutually influencing devices are getting very complex (Rader and Mahdavi 2015, Mahdavi and Rader 2014)) and graphical representations get visually cluttered. Furthermore, the rule-based control structure generation process for higher control levels is not always converging.

Related work and publications

As expected by the importance of system engineering in the AEC industry, approaches have been developed to organize and structure automation structures. Publications on automated support for the design and construction phase of Building Automation Control Systems (BACS) follow functional approaches towards an automated generation of BACS networks. These tools are based on spatial data and relate to specific products, equipment and their functionalities (Dibowski et al. 2006).

Their functional concept builds around relations between input- and output parameters as well as the description of system functions and functionality of hardware components. These approaches are driven by automation network topology and product specification and aggregate functionalities of single input/single output control (SISO) systems to a complete BACS in form of a distributed control.

Available software tools (e.g. Auteras, Trics) (Kabitzsch 2018, Tric 2018), help to establish a functional structure and working plans with informatics system centered views on data points and product-function specification/database. They support the planning and implementation of high numbers of available devices in a network, taking into consideration the devices functionality, their interoperability and complexity of the device interaction (Oezluek et al. 2009). This functional approach (DIN EN ISO 16484) supports the automated configuration of building automation networks and provides documentation according to VDI8313, VDI 3814-6 and DIN EN ISO 16484. These software packages provide state graphs to VDI 3814-6 and generate parts lists, cabling information, equipment lists and more.

Nevertheless, these tools provide valuable support for the planning and specification of network-based BACS systems.

1.2 Objectives, approach, scope and structure

In contrast, to the described functional concepts this thesis takes a structural system approach. The structural approach focuses on the system's elements and their relations and dynamic interactions. The goal is to explain the system characteristics by the structure of its elements.

Thesis Objectives

Apart from maintaining the advantages described in the previous publications, especially the straightforward mapping and presentation approach, the main objectives to an enhanced approach are:

- maintain a structural approach
- definition of a modular hierarchical zone system
  - modular integration of devices, sensors and controllers (Mahdavi et al.2015)
  - flexible for various building configurations and geometries
  - robust with respect to definition and of zones
  - adaptable to various element configurations
  - adapted for automated process, and
  - relating to control theory and terminology
- scalable mapping and control structure generation process for large multi-zone buildings with multiple systems
- integration into architectural workflows and embedding the structure and process into existing data formats and system description standards (BIM, IFC)
- a simple user interface to support the system mapping and address the definition of zones (Mahdavi and Rader 2014),
- linking with system approaches and terminology of other domains as classical control theory, system approach (IT)
- different simple and domain-specific views (simple action-effect-view, RT-view, SysML view)
- clear and comprehensible process steps, reproducible by manual steps

To accommodate for this set of objectives, especially the requested automatization and the scalability of the process, the zone concept and the control structure generation process have been newly conceived.

Proposed approach

In the sense of classical closed-loop control a mapping method and a tool for an automated generation of a hierarchical building control structure is developed.
The thesis is structured in two major sections:

- System mapping
  To reduce the complexity of the overall system, the building's system is decomposed into zones. These zones represent building physics principles and their impact-effect relationship. Building control elements are mapped to multi-parameter systems within affected physical zones.
  To link the concept to architectural entities, the derived effect-based zone concept is set in relation to geometric boundary conditions.

- Control structure generation
  The structural system model represents elementary control circuits/elements in their associated control zones. Aggregated, they form a controlled multi-parameter system.
  In subsequent process steps a structure consisting of multiple hierarchical control levels is generated. Higher controller levels coordinate the relations of control domains across lower level controlled zones.

The emanating conceptual control model allows to analyze and present control theory related details. A structural representation of the buildings' closed-loop control architecture is of special importance when hierarchical building controls or proactive building control strategies as model predictive control (MPC) are discussed.

The resulting structural model is indispensable for the discussion of control options for a real multiple-input/multiple-output system (MIMO); it goes beyond a system model consisting of aggregated single-input/single-output systems (SISO).
Conceptual models allow to discuss control theory related topics without focusing on aspects of network topology or function-based product selection. Structural system modeling underlines primary and secondary effect paths, the attenuation and interrelation of such effects.
A structural system model can also be used for verification of controllability and observability or to study controllability under system fault conditions.
The structural approach allows differentiation between controlled parameters as integral part of the control circuit and external disturbance parameters. System changes can also

refer to structural setup changes. The structural model allows to estimate such impacts on the selection of optimal control strategies.
A new method towards the mapping and the hierarchical control structure generation has been developed to meet the set of requirements, especially in view of the requested automatization and process scalability.

The new zone concept is developed as modular kit. It is the basis for the system mapping process of a building's physical effects to a set of multiple input/multiple output (MIMO) systems. Furthermore, the process relates to existing data formats and building model standards.

In a consecutive step this work develops a method, to generate a hierarchical control structure in classical control theory terms, suitable for automated processing. Subsequently, new rules for the automated and scalable control scheme generation are developed.

Advantages of such a systems-oriented approach include a better and common understanding. On one side, system complexity can be managed by system decomposition and be broken down into understandable subsystems by system modelling. On the other hand, communication and coordination among the involved engineering domains is of utmost importance. Figure 1.1 relates the proposed approaches and the management of complexity.

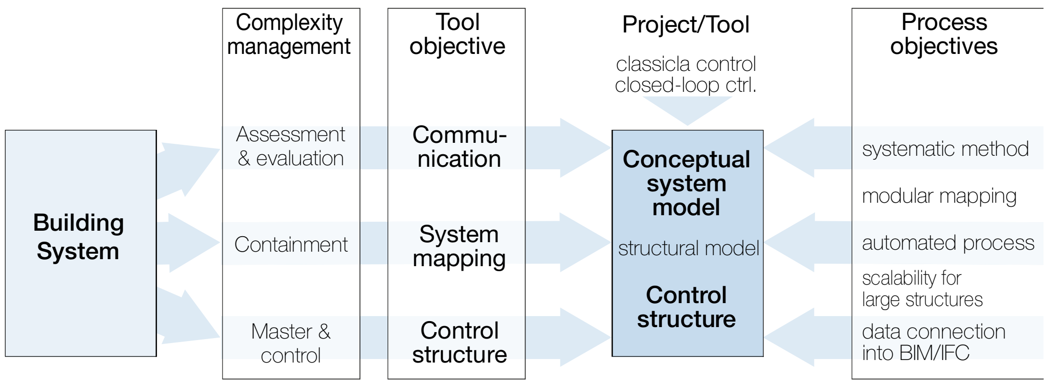


Figure 1.1 – system complexity and approach objectives

Scope

This thesis concentrates on Building Control Systems (BCS) based on a structural mapping of the building system and its manifold interactions between zones, devices, and control entities. The building control domains accounted for are:

- **thermal comfort**: heating, cooling and air conditioning systems

- **visual comfort**: lighting and daylight control
- **air quality**: CO_2, volatile organic compounds (VOCs) etc.; ventilation

Apart of the development of a technique and tool for an automatable generation of a hierarchical control structure, and to facilitate interdomain communication,

Acoustical comfort and control aspects are not considered within the scope of this thesis. It is, however, easily possible to add acoustical effects to the discussed concepts as zone concept, system mapping, effect-based structural views. The generation process for the hierarchical control structure with its comfort type related coordination levels also can accommodate for the acoustical comfort. Adding acoustical effects does not contradict with any of the presented methods (also see chapter 4.2.1).

The same stands for the impact of pressure difference as an energy type input to the system. Effects are related especially within the topic of natural ventilation. The effects are heavily affected by geometry and other fluid dynamic parameters and can only be assessed by computational fluid dynamics simulations. This work is targeting for a conceptual tool and not for a simulation tool, therefore these effects are not part of this thesis. But in principle, as discussed above, also in this case, there is no contradiction of a potential implementation with any of the presented concepts.

Thesis structure

The methodical approach towards the control scheme generation concept is shown in figure 1.2 and described in the following chapters:

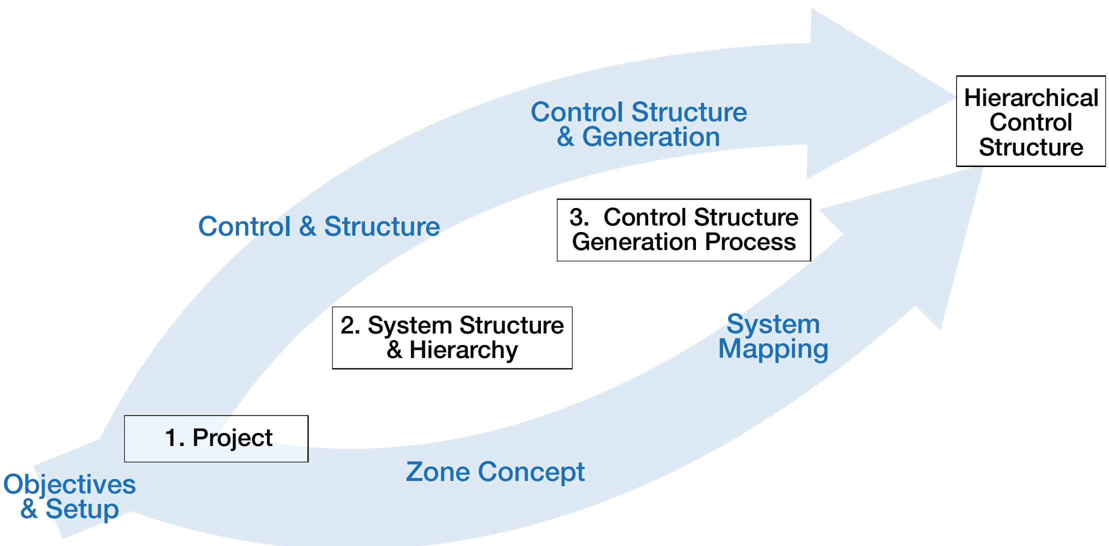


Figure 1.2 – thesis structure

1. **Thesis**
   - introduction, previous and related work, objectives
   - proposed approach, topic context
   - context: system & complexity, building control, system complexity, system engineering approaches and specifics of the AEC industry
2. **Systems structure & hierarchy**
   - zone concept, system mapping,
   - control & structure, from SISO to hierarchical MIMO control
3. **Control structure generation process**
   - system mapping,
   - generation process for control hierarchy
4. **Discussion**
   - resulting conceptual model, control and process relevant topics

The first chapter introduces the thesis, relates to previous and other related work and publications. The set of objectives is derived, and a proposed approach is presented. Finally, some topics in the immediate context of this work are presented in an overview.

The second chapter prepares the base elements for the system mapping and the control structure generation process covered in chapter 3.

The zone concept is the basis for the mapping of the building's complex physical effects. Zones allow to structurally describe the interaction between building control elements and affected zones. To describe building physics effects within structural elements, an impact- and effect-based zone concept is derived.

To project the zone concept to spatial structures as rooms, groups of spaces, building sections and to entire buildings, the link between the zone's effect-based definition and a geometry bound zone concept is examined. The necessary structured information for a spatial decomposition of the building into spaces and zones is provided by the building's representation in the form of a data model (BIM, IFC).

Control systems, their components, controlling elements and resulting control circuits are discussed in view of the subsequent mapping process and set in relation to the previously established zone concept. Simple single-input/single-output systems are aggregated to multiple-input/multiple-output systems. Approaches and aspects of multi-parameter control are presented, and hierarchical control schemes are related to commonly used representations of hierarchical structures in industrial automation engineering.

The third chapter covers the process of mapping and control structure generation itself. The process steps of the automated process from system mapping towards the generation of a hierarchical control structure are discussed in detail.

The **system mapping** as first process part is based on the BIM concept with its model based on the IFC data structure and maps the building system and system components onto modular spatial zones.

The **generation of the hierarchical control structure** follows the system mapping steps. This is a rule-based and automated process and generates a multi-level hierarchical closed loop control scheme. The multi-level control hierarchy reflects level-specific coordination and provides a structure for differentiated high-level optimization tasks. Additional process steps for the reduction of model complexity are presented.

The results of both process parts – the system mapping process and the control generation process – are presented in different control related views of the resulting system model. These views support domain specific perspectives facilitate interdomain communication and allow involved engineering groups to coordinate their efforts and yet follow their specific standards and terminology.

In **the fourth chapter** the resulting conceptual model and its advantages are reviewed. And some related system, process and control specific topics are discussed. An outlook for future work completes the presentation of this thesis.

1.3 Context

Building Automation (BA)

Even when buildings are reduced to their basic elements as external and internal walls, windows and doors, the modelling of dynamic characteristics of buildings can get elaborate. Reason are the diversified physical processes interacting with each other (Chang 1999). Furthermore, a building is a system consisting of multi-variant dynamic subsystems showing various linear or nonlinear behaviors.

The building as controlled system is also considerably impacted by disturbance variables as environmental impacts (weather conditions, irradiation…) and occupancy related effects (number, activity, interaction with the system…). These stochastic environmental and occupancy induced effects increase the complexity of control operations.
Chang (Chang 1999) ascertains that with all these interrelated effects, even a single parameter control requires a proper understanding of the interactions among related parameters. For complete building systems this is beyond the capability of manual control efforts.
This, and the available technology led to automated building control systems, beginning with simple thermostats. Readily available electronics and information technology extended the functionality of digital building control systems for the control of heating, ventilation, air-conditioning (HVAC) and illumination. Further integration into building automation systems includes security and safety systems. These systems are subsumed under the field of 'Building Automation' (BA).

Building automation (BA) provides the technology and equipment for autonomous control of building related technical processes and systems. BA refers to the entity of monitoring-, managing-, control-and optimization equipment in buildings and represents an important element of technical facility management. The objective of BA is to automatically execute process sequences and to facilitate their operation and monitoring.
The term ‘building automation’ spans across the fields of automated control, open-loop control, control logic, optimization, monitoring and interfaces to the operation of technical building equipment. It also includes safety and security functions and can result in highly complex systems.

Building Automation and Control Systems (BACS)

Building Automation and Control Systems (BACS), as a subcategory of BA, emphasizes control- and dynamic's aspects within building automation. BACS refer to hard- and software systems and extends into other control related areas of BA as supervision, monitoring and optimization of building- and facility systems.

The principal objectives of BA & BACS are to operate a functional building at minimum energy consumption and to provide an optimal working environment. For residential buildings the focus is on providing a comfortable living environment. The core functions of a building automation control system thus include comfort- and energy control (e.g. Heating, Ventilation and Air Conditioning, HVAC). And it provides the infrastructure to optimize the operation of buildings in terms of energy demand, operational cost and efficiency.

Building control

Building Control Systems (BCS) and control engineering is an integral part of modern automatization technology and thus constitutes a central module within the building automation (BA) and BACS.
Control engineering is a discipline focusing on a wide range of dynamic systems. It requires a good knowledge of the physical systems concerned, the implemented technologies, and the equipment used. Hence the need for close cooperation and communication among all directly involved engineering domains.

Building control engineering is a multi-disciplinary engineering domain. The principal players and engineering domains involved are:

- Mechanical-, Electrical engineering and Plumbing (MEP) industry
- Information technology (IT) is responsible for the processing and transmission of non-physical information. This includes software and respective hardware and all functionality based on digital processing.
- Control engineering domain, with the task to maintain specific output parameters of a dynamic system within defined limits. Implementation of control algorithms fall into the IT domain, the hardware for sensing, signal transmission and -processing into the electrical engineering area and the actuators/devices, depending on the physical nature of their output into the mechanical- and/or electrical domain.
- Architecture is responsible for the spatial boundaries. Design influences the underlying dynamic characteristics and has an impact on effects of stochastic disturbances (e.g. irradiation through windows, material selection).
- Building physics addresses internal and external impacts to building performance and supports building design in terms of energy efficiency and comfort objectives.

Control in the sense of 'classical control' or 'closed-loop control' is a process to attain or maintain a desired system condition; this is achieved by continuously comparing the controlled process output parameter with a command- or reference-value. The controller influences the dynamic system to bring and/or maintain the respective controlled output parameter to the target value despite of external perturbations of the system.
In the context of this thesis, the term ‘control’ is used for closed-loop control in the sense of classic automatic control theory, control circuits and respective definitions according to DIN IEC 60050-351 (DIN IEC 60050-351).

The employed building control systems act on numerous dynamic subsystems of different physical nature. Control systems include controllers for heating, ventilation and air-conditioning (HVAC), lighting systems, shading systems, systems in the Mechanical, Electrical and Plumbing industry (MEP). The controlled dynamic systems consist of entities as internal spaces, elements of the building structure and envelope (e.g. walls, windows).

The control objectives relate to human comfort, economic and energy implications and are primarily acting on comfort parameters for thermal-, visual- comfort and air quality while optimizing energy performance.

AEC industry

Specifics of the Architecture, Engineering and Construction industry (AEC) are the considerable number of domains involved throughout the entire life cycle of building projects. The number of participating domains constitutes one of the drivers towards increased system complexity. Trans-disciplinary or a well-working interdisciplinary project management approach is an organization form to face the challenges of increasing complexity in building design and building control (Lam et al. 2004). The complex project and development processes require a high level of cross-functional cooperation and coordination as well as elaborate data exchange tools for efficient communication between the involved domains and crafts.

The AEC industry sector therefore has not only relied on the technology developments within the participating domains but also puts emphasis on enhancing their multi- and interdisciplinary communication and workflows. In early stages, computer-aided design was introduced to provide consistent 2- or 3-dimensional model views across the industries. The AEC industry also adopted system engineering methodologies and continued their efforts towards a more efficient and integrated workflow by introducing the unified digital process concept of Building Information Modelling (BIM).

The building information modelling (BIM) has gained importance as an innovative process to design and manage AEC projects. The BIM approach and its data structure, as a collaborative and transdisciplinary data repository, improves building development and building operations processes. The underlying digital building information model characterizes, among others, the geometry, spatial relationships, geographical information, quantities and properties of building elements, cost estimates, material inventories, and project schedule.

Complexity of buildings

From a system view, a building and its subsystems represent a multidimensional interaction field with a wide variety of impacting effects and activities:

- building characteristics influenced by physical processes interacting with each other and with the environment (Halonen et al. eds 2010)
- multi-variant dynamic subsystems with various linear and nonlinear behaviors
- impact magnitude of disturbance variables as environmental and occupancy parameters and occupancy control operations
- multi-domain engineering influence across AEC domains and beyond (AEC, MEP, IT, Electro, Mechanical, Architects, …)
- numerous building automation subsystems and control equipment, elements and devices
- challenging and conflicting objectives for control and optimization

Figure1.3 shows the drivers of complexity in building systems.

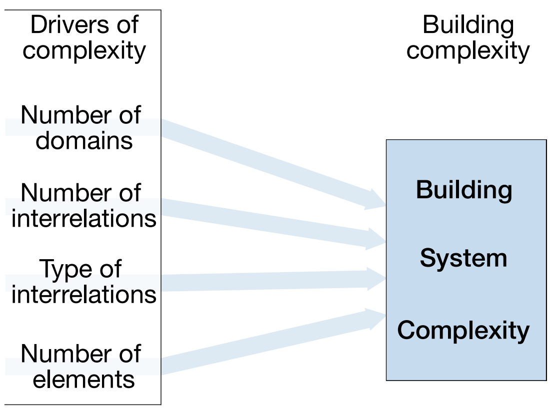


Figure 1.3 – drivers of building complexity

System complexity

The term 'complexity' in context of systems refers to an internal structural characteristic; the complexity of a system increases with the number of system elements, the number of interactions and interdependencies of its elements and the functionality of these interactions. Complex systems require extensive control actions and/or knowledge of the underlying process mechanisms (Haberfellner et al. n.d.).

Complexity can be seen in view of different aspects (Helenbrand 2013)

- **Structural complexity**
  results from the number and diversity of its elements and relations and the interdisciplinary interrelation of its elements. Complexity not only grows with the number and type of its elements and subsystems, but also with the number of involved parameters, interfaces, boundaries and conditions.
- **Coordination complexity**
  Further drivers of complexity in course of the process are the involved or participating domains and the process organization. It describes the complexity of communication, information sharing and information dependency among teams and coordination efforts emanating from teams working on an interdependent framework of components (Yang et al. 2015, Yang and Zheng 2016).
- **Dynamic complexity**
  stems from the number and kind of system states and their interactions in view of the variability of its structure.
- **Aggregated complexity**
  deals with the coaction of single elements, aggregating a system with complex characteristics, coaction and relations of the system elements, the internal system structure and the resulting system performance.

Management of complexity

According to Eben and Lindemann (2010) and Lindemann et al. (2009) the management and control of complexity requires understanding and knowledge of the system and its structure. This approach comprises the following sub-strategies:

- **Assessment and evaluation** of complexity including the collection of necessary data, system dynamics, effects and their interrelations as well as their suitable modelling and subsequent analysis and visualization.
  This part will be discussed in chapter 2, ‘zone concept & control structure’.

- **Containment of complexity** by reduction and decomposition with methods as modularization, hierarchization, partitioning and integration.
  Chapter 3 'system mapping' relates to this sub-strategy.
- **Master and control of complexity** referring to actions taken to run systems with support from other technical processes (automation, control).
  Chapter 3 'control structure' relates to this sub-strategy.

The proposed methods to manage complexity in context with building systems are shown in figure 1.4.

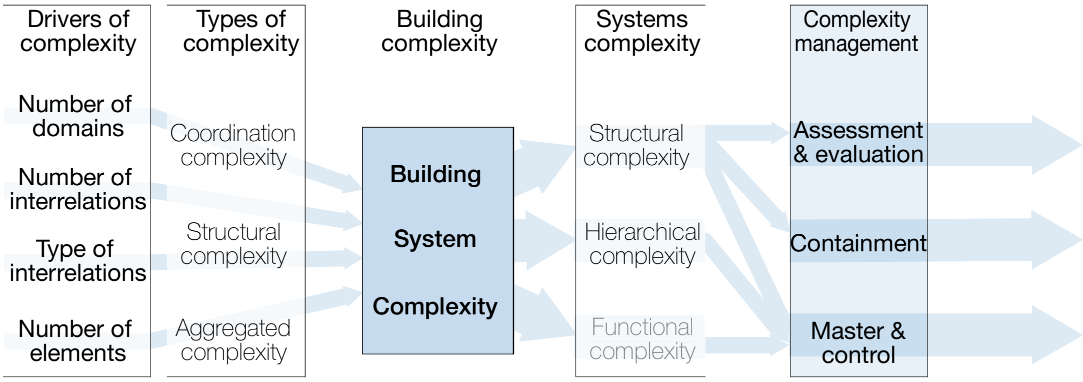


Figure 1.4 – management of complexity

System concepts

The system notion covers three aspects: the functional, the structural and the hierarchical system concept. Figure 1.5 indicates the principle characteristics of these system concepts.

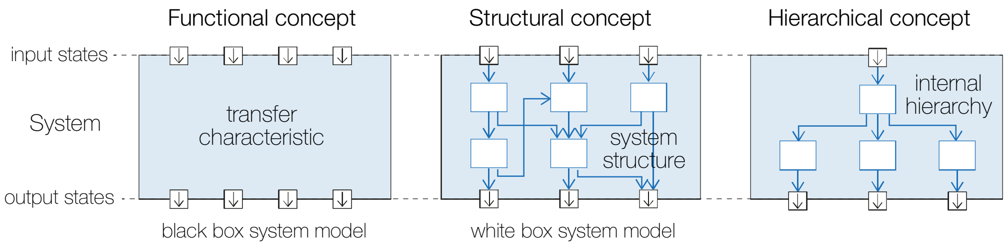


Figure 1.5 – system concepts (Ropohl 2009)

- **the structural system concept**
  is referring to the system as an entity of interconnected elements. The structural approach focuses on the elements and their multitude of interrelations and dynamic interactions, leading to diverse system characteristics. The objective is to describe the system behavior and how a system output is generated from an

input setting, by the structure and the dynamic interrelation of its elements (white box concept).

This approach is examining and describing a system based on the question **'what is it?'**.

- **the functional concept**
  is referring to a system as a black box with its input parameters and output states. It characterizes the system in the form of a transfer function by observing the relations between its properties from an external view, disregarding the inner system structure. Among those properties to describe a system are the input parameters and the output states.

  This is studying a system based on the question **'what is it doing?'**.

- **the hierarchical concept**
  is emphasizing the fact that the parts/subsystems of any decomposed system are again representing systems, thus establishing several levels of a system hierarchy. This approach allows level-differentiated views without losing the overall context (Storchi and Wiesendanger 2003). Moving down in a system hierarchy provides a more detailed explanation of the system, whereas getting to higher system hierarchy levels gives a broader understanding of its relevance and its delimitation from higher or meta systems and the environment.

The focus of this work and the derived process steps follow the structural- and hierarchical aspects of system engineering.

System models

System engineering is coordinating the inter-domain project activities using a defined collaboration framework with a structured data set. Project related data, specifications, requirements and information are defined in a common data vocabulary. Such data framework is called a 'model' and refers to conceptual models as compared to e.g. physical- or mathematical models. A model is a representation of an entity. Models allow to abstract selected system characteristics, to focus on a limited subset of the represented system and to study and understand certain properties (Mahdavi 2004) and to examine variants and modifications to the existing system (Storchi and Wiesendanger 2003). Furthermore, system models facilitate the communication and coordination among team members and involved domains.

A central conceptual model collects project and system data, dependencies and relations and links them with domain specific modelling tools. These conceptual models constitute a unified project repository and provide an interdisciplinary system view. Its data is shared across domains, keeping a consistent notation and defined relationships throughout the available views. The different aspects, perspectives and filtering options allow domain specific views in their specific standards and terminology.
In case of systems with numerous or complex relations such models are developed and employed to provide a better or common understanding of reality.

Relating model categories with system concepts, building models can be grouped in categories:

- white box models:
  models are based on prior knowledge of the internal physical systems and their interactions.
- black box models:
  models based on the response of output states to a set of input values, without knowledge of the systems internal structure or physical interrelations
- grey box models:
  these models are based on some knowledge of parts of the internal system. Parameters of these models are adapted to fit measured input/output characteristics/states

Model based System Engineering

A System Engineering interdisciplinary approach using repository-based modelling tools and relating to system data models (digital models, conceptual models) is referred to as Model Based System Engineering (MBSE). MBSE is a system engineering methodology centered around the creation and evaluation of conceptual system models.

The underlying system data model allows to extract and maintain precise and distinct views of its subsystems, their behaviors and interactions in different levels of abstraction. The data consistency and completeness of the system data model closes the gap between the different domains and their respective workflows, processes and tools. The MBSE approach aligns product requirements, physical characteristics and system/subsystem performance through the design and life cycle process. MBSE with its centralized data model replaces manual document-based information exchange and thus increases the productivity of the development process and projects with large teams. Figure 1.6

shows the concept of a shared data model as applied in model-based engineering in context of a transdisciplinary organization scheme.

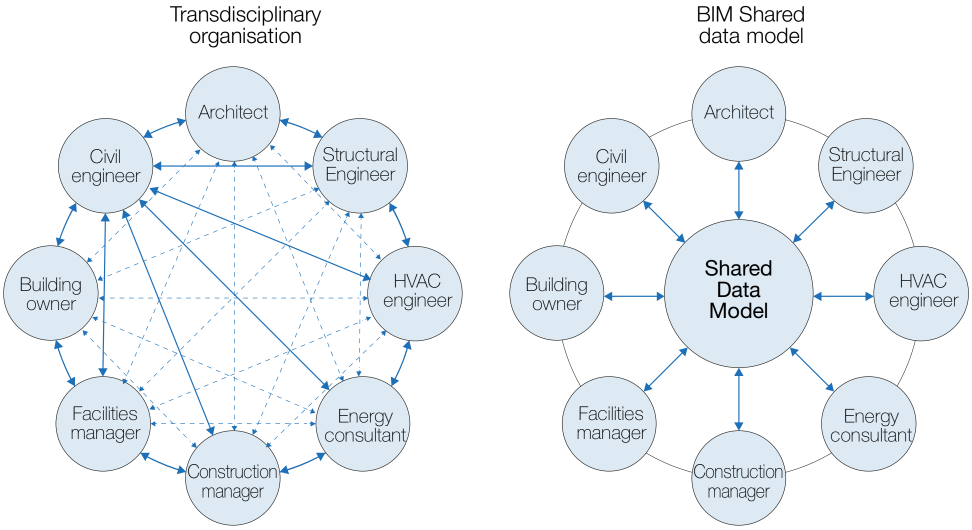


Figure 1.6 - shared data model (Claus and Schuller 2015)

BIM

In the AEC industry the data modelling concept is referred to as 'Building Information Modeling' (BIM). BIM describes a computer aided process for optimal planning, construction and management of buildings in all phases of the life cycle. It supports connectivity of multiple parameter categories, including project information, assembly specifications, building operation, and building users.

The conceptual building data model makes all current and relevant data available for all participating domains and teams and enhances the information exchange between involved engineers. This allows coordination across different domains and crafts and enables all involved domains and stakeholders to access data from a single and maintained source.

All building relevant data is stored, combined and maintained in a centralized digital model, the commonly shared building information model. The building data model supports different domain-specific views and data retrieval of the total building database on different aggregation levels and provides domain-specific information.

The model uses a data model based on the Industry Foundation Classes (IFC) data model. Data from domain specific models are translated into the IFC's descriptions and made accessible across all involved domains.

IFC

The Industry Foundation Classes/IFC (buildingSMART 2018) refer to a standard defining an interchangeable data format for computer models in Architecture/Engineering/Construction (AEC) domains. (Lam et al. 2003). The objective is to provide the necessary interoperability within the AEC industry.

IFC is an open file format specification (DIN EN ISO 16739) and defines a data model in an object-based file format, managed by buildingSMART (buildingSMART 2018). The IFC data model serves as a commonly used collaboration format in Building Information Modeling (BIM) projects and facilitates the consistency and exchange of data between involved domains and domain-specific applications.

The conceptual data model is capable of mapping a wide range of building related elements, functional and behavioral relationships and materials. The IFC model includes a range of element description concepts including: spatial elements (space, storey, …), building elements (doors, windows, walls), shapes (walls, pipes), equipment (fans, pumps) and relations between elements. The entities are put in relation to each other and thus establish a hierarchical structure. Non-building element classes refer to e.g. actors (people, organizations), costs, work plans and schedules and resources in a facility management context (inventories, maintenance histories).

SysML

The System Modeling Language – SysML (SysML 2018) represents another type of modeling language. SysML was established by the Object Management Group (OMG 2018) based on the widely used and software oriented Unified Modeling Language (UML) and is specialized for modeling in system engineering. SysML and its base is originally coming from the IT- and automation industry and addressing requirements for mapping dynamic and functional characteristics, processes, behaviors, and their relationships.

SysML is currently one of the most widespread modeling languages. Its focus is on the description of system characteristics in different graphical views. The advantage of this language is the capability to model various system aspects, from topological features to operational and functional characteristics. Such systems can comprise hardware, software, information, personnel, procedures and facilities.

SysML is a general-purpose graphical modeling language and supports the specification, analysis, design and verification of complex systems. With its graphical representations it is capable of representing the main aspects in a flexible way and to cover different domain-specific modeling techniques.

Design oriented graphs are the requirement graph (req) and block definition graph (bdd) serve to document the design process of the system, whereas the internal block diagrams (ibd) and parametric diagrams (par) are analysis oriented. Further graphical representations in the form of diagrams include behavior diagrams and structure diagrams. With the thesis's focus on systems and their structure, the structural representation group, as block diagrams (bdd), internal block diagrams (ibd) and parametric diagrams (par) are of interest.

IFC vs/and SysML

For a building related system engineering approach, both IFC and SysML show strengths and shortcomings.

Building Information Modeling (BIM) started from a focus on static geometric models. It focuses to improve collaboration in the design and construction phase of buildings and extends to project management throughout all life cycle phases. The underlying Industry Foundation Classes (IFCs) data model definition covers typical building concepts, including building space hierarchy, building elements (doors, windows, walls) and their shapes and relations, equipment (MEP, HVAC), interior elements and a wide range of building project related elements. IFC also focuses on the hierarchical interaction between building elements and infrastructure and provides elements for modeling in building design, construction, and facility management.

This data model is a rather static description and shows shortfalls on dynamic and functional system characteristics and their interdependencies (Geyer and Buchholz 2010).

The System Modeling Language (SysML) on the other hand, focuses on the definition and description of dynamic system- and functional characteristics and provides different cross domain views. Its strength lies in the versatility to define structural, operational, functional system and dynamics features.

Combining the advantages of these two MBSE modeling approaches, as in BIM, the IFC and SysML modelling languages can enhance each other. SysML adds additional functional aspects to the geometry- and element-based view of current IFC and it links the definition of system requirements and supports the modelling of dynamic impacts/affect relations with respective flows of energy, mass and information.

A combination of the BIM/IFC and SysML modeling approaches increases the multidisciplinary information horizon and allows to integrate AEC industry domains with system domains as control engineering, IT and automation domains.

2 System Structure & Hierarchy

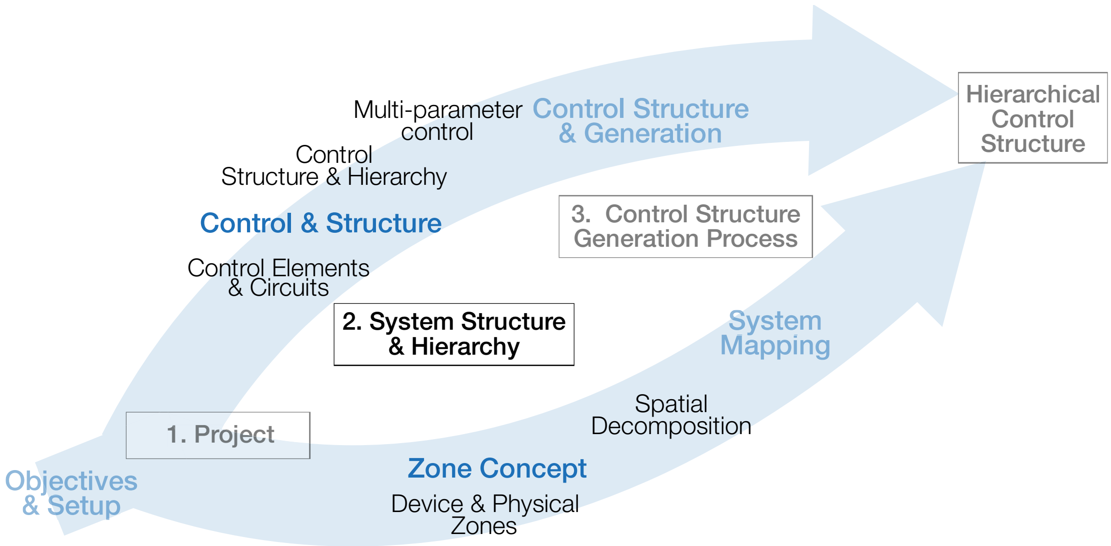


Figure 2.1 – structure chapter 2

This chapter establishes the ground for linking physical effect relations to a zone concept as well as control interventions to classical type control structure.

Zone structure

In the first section of this chapter a modularized and scalable zone concept is presented. The concept maps building control elements and physical systems to effect-based spheres. This allow a systematic compartmentalization and structural modelling of a building and its control system into flexible sub-entities.

The notion of zones refers to a structural and hierarchical concept, which serves as basis for the subsequent control structure generation process (see chapter 3.6). The mapping relates a physical effect-based structure to classical control schemes. The zone concept's modular framework is essential for an automated mapping process as described in chapter 3.4 and at the same time facilitates the understanding and human intervention.

The 'zone' concept thus provides the framework for the functional mapping of the building's complex structures. The mapping process centers on the interactions between building control devices, their respected areas of intended impact, external disturbances and effects between zones. The zone represents the target of control impacts and a container for resulting physical effects.

From the underlying concept, zones are not necessarily linked to architectural entities as rooms. The zones are defined by physical effects and represent flexible entities. These entities may however be associated with parts, whole or aggregations of architectural spaces. To that, the relationship between an effect-based impact zone of active components and the geometrical building structure is examined. Such reference is necessary to relate the physical effect-based zone concept to spatially organized data models commonly used in the AEC industry.

Control structure

The second part of this chapter covers classical control aspects with the previously derived physical zone as the controlled element. It departs on selectable modular control elements and develops to basic control circuits. Simple single-input/single output systems are aggregated to a multi-parameter hierarchical control concept.
The control structure is compared to standard hierarchical feedback control structures as well as to related strategies in automation engineering.

This part thus develops the basis for the mapping process and the subsequent generation of a control structure. An established relationship of the zone concept with architectural entities allows to establish a workflow using existing building data models. The modular zone concept facilitates user interactions, base modules with predefined effect paths for standard device types assure a complete set of the basic building physics effects.

Views are introduced to represent the simple decomposed subsystems, all the way to agglomerated and complex multi-parameter systems. The system representations also cover domain-specific approaches and views for control-, automation-, IT- and building engineers; the views include graphs, adjacency matrices and SysML-type graphs.

2.1 The Zone Concept

Structural Mapping

One way to contain a building system's complexity is to decompose big structures into smaller and more accessible subsystems. These building subsystems are described in terms of zones; they contain abstract model elements and a representation of their physical cause-effect relations and interdependencies. This mapping results in a structural model of a building's system.

Zone concept

The zone concept combines the

- decomposition of a complex system into delimited areas/spheres, subject to specific system impacts
- mapping of involved system elements together with their impacts and effects to these areas.

The structural and hierarchical notion of zones constitutes the basis for the subsequent control structure generation process. The zone concept also links an effect-based system representation to classical control approaches.

The strictly modular framework is essential for an automated and scalable mapping process. At the same time, it facilitates the understanding and manual intervention.

Zone mapping

The zone mapping is based on two primary zone types and an aggregated zone. The primary zones and their elements are:

- **Device zones (DZ)** represent the effect of control actions within their intended impact sphere.
- **Physical zones (PZ)** are defined as an aggregated set of overlapping device zones.

A next level of zone aggregation is represented by a **Control zone (CZ)**, aggregating the first level of:

- controlling elements, the
    - device controllers and
    - devices, and the
- controlled system
    - one physical zone (as aggregation of device zones).

The relation of these 3 interlaced zones is depicted in figure 2.2.

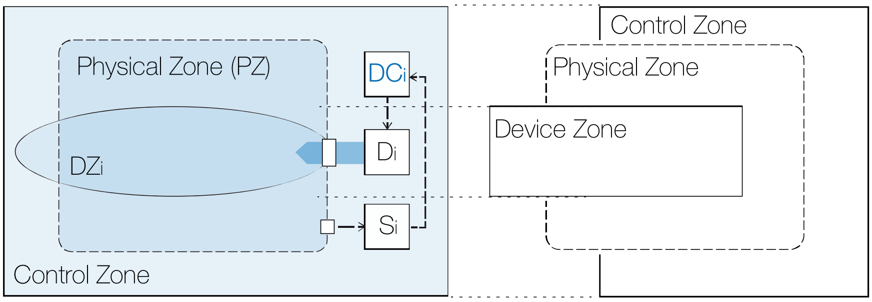


Figure 2.2 – zone mapping

To map the effect of controlling device actions on their affected physical zone and to generate a control model it is necessary to build on physical cause-effect relations.

The zone concept and the mapping process is not necessarily linked to architectural entities as rooms. A zone as a flexible entity however can be projected to a building's constituent spaces and elements (Mahdavi et al. 2015). Physical zones and respective control zones will be used to relate the mapped physical effects to architectural entities.

Zone concept - requirements

The previously published system description approach has shown good acceptance amongst users for its straightforward and simple scheme (Mahdavi et al. 2015). This mapping defines a direct action-effect relation between devices and the sensors measuring their impact.

This zone concept will be extended for a scalable and flexible mapping process.

These adaptions are necessary for the cross-domain understanding of the concept and for the automated generation process of a hierarchical control structure. The underlying zone concept and its description throughout the process steps is more elaborate and offers more system options. And it is designed for a higher degree of interrelations, to make the system description scalable and to allow an automated process. Nevertheless, the process will maintain the straightforward initial dataset as well as produce a similarly clear result view (Mahdavi et al. 2015).

Figure 2.3 depicts such a simplified effect path view on the right, as well as the representation in the form of an impact zone.

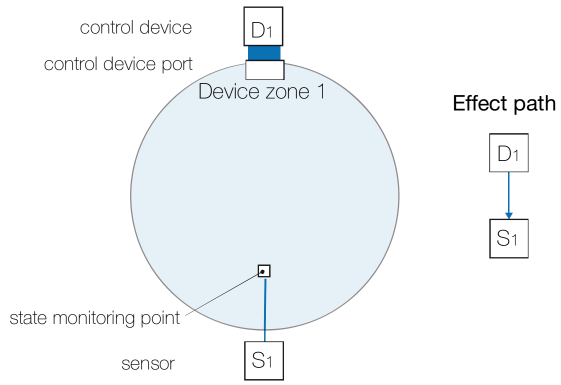


Figure 2.3 – zone, base representation

The pursued extended zone concept has to fulfill requirements as:

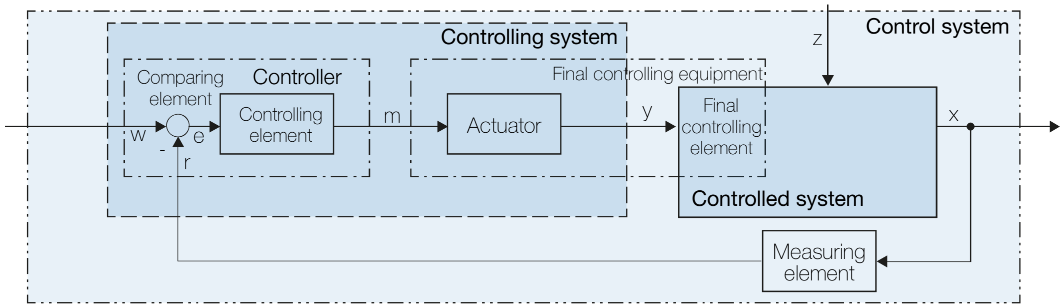
- the request for automated processing calls for a modular concept.
- the modular concept needs added capabilities for mapping interrelations between zones.
- to master large multi-zone buildings with multiple systems, the sought scalability of the process requires a system representation in an abstract mathematical form, e.g. in form of a matrix.
- for further discussions on control structure and hierarchies, the zone concept needs to be adapted to classical control theory terms.
- various building system components, characteristics and configurations demand for adaptability and flexibility of the targeted modular system
- a flexible and robust zone definition (extent, number) to yield comparable structural results with freely selectable system decompositions
- structural concept that is transferrable to other engineering domain specific approaches and terminology.
- provide simple and domain-specific views, from a simple action-reaction/device-sensor (D-S) relationship graph (see figure 2.3 right) to more involved graph- and matrix representations, control views and SysML-type views.

2.1.1 Device Zone

Device (D)

A controlling device – in this context also related to as ‘device’ represents the 'final controlling equipment acc. to IEC 60050 (DIN IEC 60050-351). It is a technical equipment or system, designed to deliver a quantity of energy and/or mass to a passive-/physical zone as controlled system (see figures 2.3 and 2.4).

Its function is activated by a controller output variable and/or an actuator. Typical examples of devices are heaters, radiators, windows, etc.



w reference variable
y manipulated variable
x controlled variable
m controller output variable
r feedback variable
z disturbance variable

Figure 2.4 – control circuit ((DIN IEC 60050-351)

In this thesis the term 'device', or 'controlling device' comprises:

- an actuator (if present) “generating the manipulated variable required to drive a final controlling element from the output variable of the controller” (DIN IEC 60050-351).
- the ‘final controlling equipment’. Because of its dynamic behavior it is usually considered as part of the controlled system. It manipulates the mass or energy flow to the controlled system.
  As this thesis's structural approach does not focus on the dynamics but centers on the structure and effect paths of the system, the final controlling equipment is, for modularity reasons, considered to be part of the controlling device. This definition has no effect on the control structure generation process (chapter 3). The function level of ‘devices’ will be later eliminated for the reduction of complexity and for graphical display reasons (see chapter 3.5.1).

Taking the example of a radiator as controlling device, the motor valve represents the actuator; it regulates the amount of heating fluid for the radiator. The radiator itself converts the energy of supplied heating fluid into radiation- and convective heat, resulting in a temperature rise within the impacted space.

For this concept, the actuator/valve and radiator as final controlling equipment are combined in one abstract component, the 'device' or 'controlling device' (D).

The presentation of IEC 60050 (DIN IEC 60050-351) with the adaptations as described above reflects the setup for this thesis and is shown in figure 2.5.

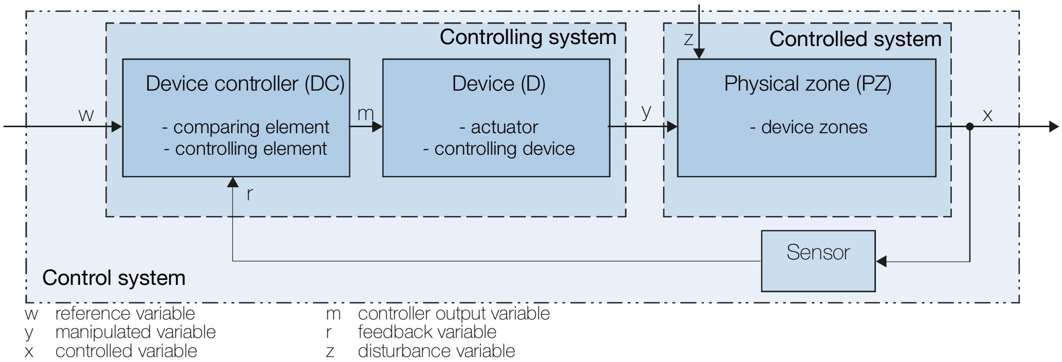


Figure 2.5 – control circuit, modified device interfaces

The term 'device' is not limited to one physical device (set of actuator and final controlling element), but a device can consist of a commonly activated or controlled set of devices. An example of a device set is a set of lamps activated by one switch (actuator).

The selection of device components is done by their intended effect, dynamic characteristics, for their energy sources, etc. The specified requirements may be covered by various technologies or types of devices, by groups of employed devices of a kind, or by a combination of different devices, with their primary and secondary effects adding up (see table 2.1 – primary and secondary effect of devices).

Table 2.1 – devices and primary/secondary effects

Devices	Effect primary/secundary	thermal		visual		air qual.	
		temperature	rel.hum.	luminance	glare	CO2	air quality
heating/ cooling	radiator/convector	P	S				
	radiation heating	P	S				
	floor heating	P	S				
	activated ceilings	P	S				
	HVAC	P	P			P	P
shading	external shading	P			P,S		
	external louvers				P		
	internal louvers	S			P		
lighting	lighting			P			
ventilation	windows	P	P			P	P
	ventilation	P	P			P	P
disturbance parameters	occupancy (number)	P	P			P	P
	occupancy (activity)	P	P			P	P
	climatic impact	P	P	P	P		

A single device may also have an impact on more than one physical zone. This is the case for e.g. outside shades extending over several windows, with the windows assigned to different physical zones. These cases are covered in chapter 2.1.5 - special zones.

Device zone (DZ)

The area of intended impact of a device is the device-controlled zone and is referred to as 'Device Zone' or 'DZ'. The device zone represents the controlled element of a control system (see figure 2.7a).

A device induces energy or mass (with positive or negative algebraic sign) into its intended activity environment. E.g. a heater supplies energy in the form of radiation (energy) and convection (mass/fluid transport) to its environment, a lamp emits radiation (energy, in form of visible light) onto a working plane and thermal energy to the air, etc.

The above described general concept relates the action of an active element (controlling device) to a physical impact within its intended impact sphere (device zone).
These spheres are device-centered and effect based and therefore are referred to as 'device zones'; this general concept does not relate them to architectural entities.

The device zone can be imagined as a 3D sphere, delimited by an iso-surface of a certain impact magnitude. The DZ can also relate to a 2-dimensional measuring plane (e.g. illumination on a work plane) as shown in figure 2.6 or to a 3D-resembling construct of a compiled stack of 2D measurement planes.

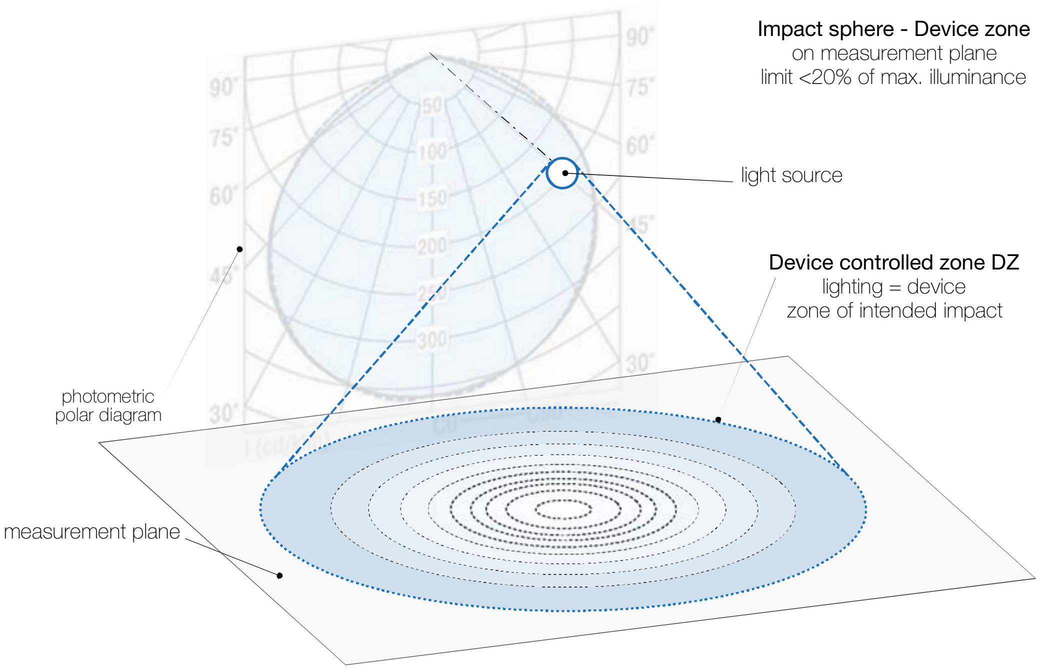


Figure 2.6 – device zone

The abstract 2- or 3-dimensional shape of the impact area depends on the

- type and characteristic of the device,
- principal physical impact type (energy/mass),
- effect propagation mechanism,
- defined boundaries (limitational impact magnitude) or existing propagation discontinuities

The device zone's sphere of influence is not necessarily a static entity but can be changing over time, e.g. variant intensity and angles of incidence of irradiation through a window.

Device zone – extended system and definitions

Mahdavi et al. (2015) proposed a convincingly uncomplicated action to response (device-sensor) mapping concept (see figure 2.7a).

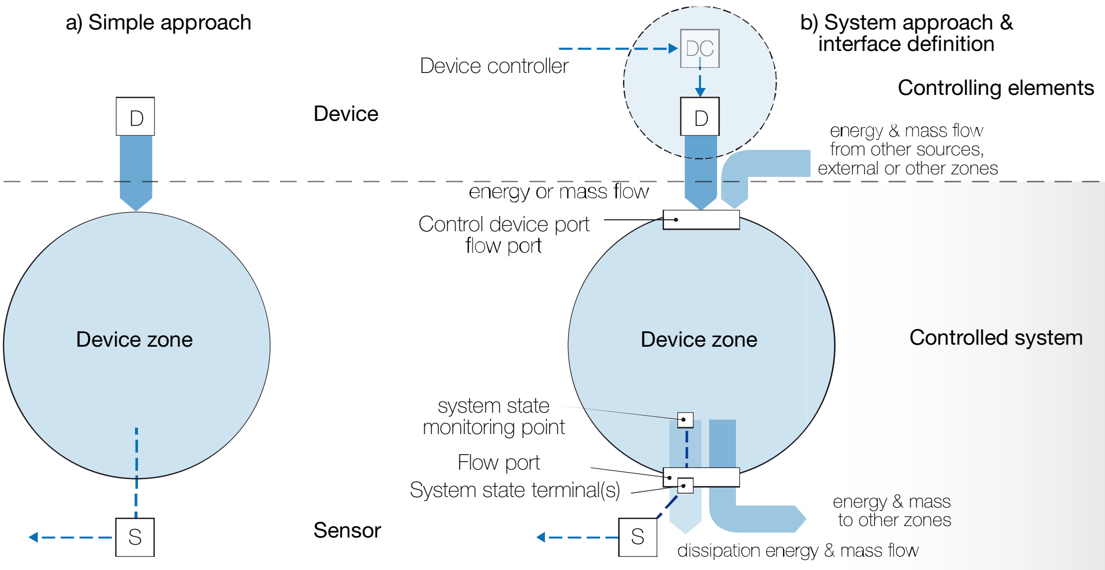


Figure 2.7 – device zone, extended system view

To enhance that approach towards a system and control related description and to prepare for mapping of interrelations between zones, additional related terms are defined (see figure 2.7b) without changing the underlying concept (figure 2.7a).

Controlling elements	The controlling elements of a control system include:
Device Controller (DC)	The device controller (DC) operates the device (D). It is assumed that every individual controlling device is operated by a device controller (DC).
Device (D)	The device is the technical equipment inducing quantities of mass and/or energy and is as-signed to influence certain system states within the control zone.

Controlled system	The controlled system relates to a technical/physical process. The controlled system is represented by the:
Device zone (DZ)	or 'device-controlled zone' corresponds to the sphere affected and controlled by the control devices action

Ports and terminals	depict the physical interfaces of the controlled system (DZ).
Ports (energy/mass flow)	A port depicts the energy/mass flow interfaces where energy or matter is transferred from one element or subsystem to another element or subsystem (Karnopp et al. 2000).
Terminal (attributes, parameters)	is the interface node where information on attributes or parameters are made available to other system elements and structures.
Nested Ports (flow- and state properties)	The exit flow port as the interface for mass/energy flow is depicted as a nested port (SysML term), providing flow properties as well as state information. E.g. it is assumed that air extracted from the zone has identical characteristics as the air within the zone; the properties (temperature, humidity, CO_2 content, etc.) are accessible through the state terminals nested within the flow port. In terms of Karnopp (Karnopp et al. 2000) this concept refers to the terms of 'through-variables' (flow properties) and associated 'across-variables' (state variables).
Control device port	Is the interface of a device to its device zone and where energy or mass is induced into the device zone.

Sensor mapping	
Sensor (S)	Monitors the value of a controlled variable. The respective parameter is measured within the device zone at the monitoring point and provided at the respective state terminal. The sensor as system element is here considered as a separated element. This to align with common control views and for process reasons (see node reduction, chapter 3.5.1).
System states	State variables describe the physical condition of a dynamic system. E.g. air within the control zone can be characterized by state variables as temperature, humidity, CO_2 content etc. The states are the system response to interactions of devices, external impacts and disturbances (e.g. ventilation, occupancy effects).
System state monitoring point	Represents a virtual position of the measuring element within a device zone or along a mass/energy flow exiting a zone (e.g. in a ventilation duct extracting air from a zone). Virtual sensors combine state signals to a virtual sensor value and hence do not refer to an actual position within the zone.
System state terminal	is the interface where system state information (e.g. measured parameters) are made available

Flow- and state concept

With the above definitions the zone concept combines two system aspects into one representation.

- **Flow concept**
  Changes in a device zone can be expressed in terms of added/removed energy and/or mass. The balance of energy/mass flows through in- and out-ports must satisfy the law of conservation of energy and the principle of mass conservation. This aspect is important when for interlinking zones through energy/mass transfers.
- **State concept/control system aspects**
  Control parameters (manipulated variable) as signal inputs to a controlled system and its output parameters (controlled variables) do not necessarily refer to an energy/mass flow but reflect various system states. These states can be attributes or properties of the involved energy/mass flows.

In the above terms the aspects of the flow concept are described with 'ports', whereas the information on states is passed through 'terminals' (see above)

Figure 2.8 shows these concepts, the flow concept in the physical view and the state concept in the control view.

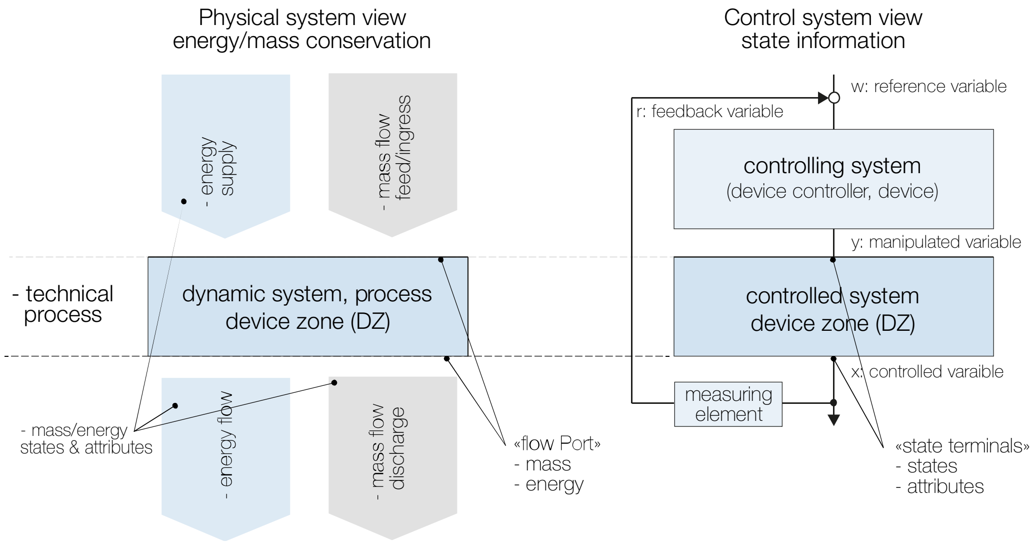


Figure 2.8 – device zone, physical & control view

In the context of defining an impact zone it is worth mentioning that the sphere of influence is not necessarily a static entity but can be changing over time, e.g. the influence sphere of external irradiation through a window, with the light beam/sun rays having time variant intensity and angles of incidence.

2.1.2 Physical Zone (PZ)

In the context of building control there is rarely a space affected by a single controlling device only; building sections include a considerable number of controlling devices and overlapping device-controlled zones. Figure 2.9 shows a setup with 2 overlapping device zones).

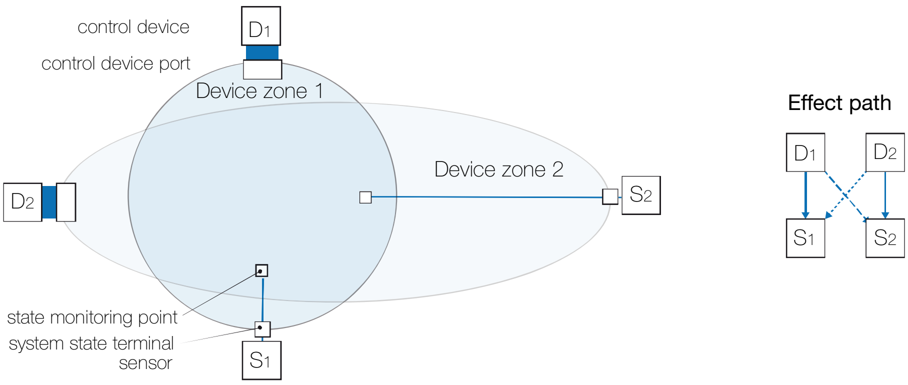


Figure 2.9 – physical zone, multiple device zones

Physical zone as aggregation of device zones

The overlapping device zones are of particular interest for the design of a suitable control strategy.

The physical zone (PZ) is introduced as a new element; the physical zone element consists of one or several device zones. The PZ thus describes the dynamic effects and interrelations caused by the action of one or multiple controlling devices.

The abstract shape or extent of a physical zone relates to the shape and extent of the impacting device zones. In case of a single device the extent of the physical zone can be, but not necessarily is identical with the impacting device zone.

An example configuration as shown in figure 2.9 can be broken down into several sub-zones with differing device impact situations (figure 2.10a).

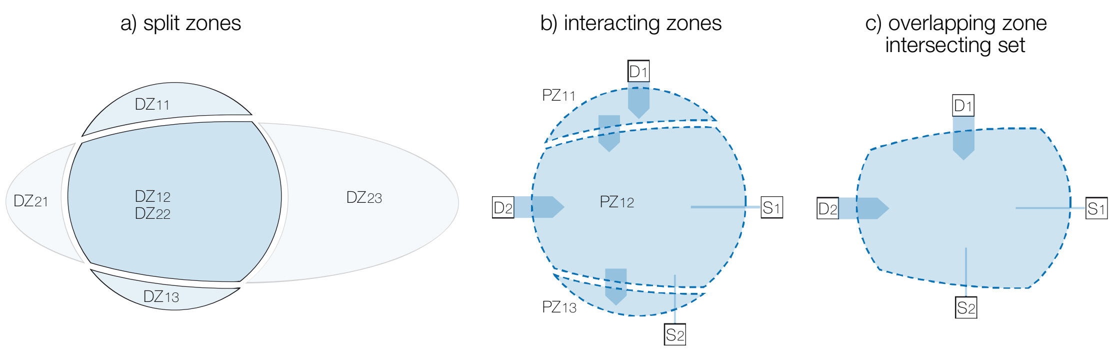


Figure 2.10 – physical zone configurations 1

For the setup of a physical zone the position of the actual sensors (their position is related to the respective system state monitoring points) is of decisive importance. States in subareas without any state monitoring point (sensor position) cannot be accessed and there is no mesurable control related impact. Such subsections can be attached to other sections or eliminated in the agglomeration process of a PZ.

The interesting area for control system design is the intersecting set of the device zones. Based on the monitoring points in the example, the four non-overlapping subzones could be neglected leading to a configuration as shown in figure 2.10c.

A physical zone can also be set up as a set union of device zones (see figure 2.11d). With this setup it is assumed that the entire space shows identical states as at the monitoring positions. That is also where the sensors are located.

Furthermore, the physical zone can be defined by a subset of the interesting sphere of overlapping device zones (see figure 2.11e) or as an aggregate zone, consisting of several overlapping and/or non-overlapping device zone clusters (see figure 2.11f). These cases are of special interest in context with geometries of building entities.

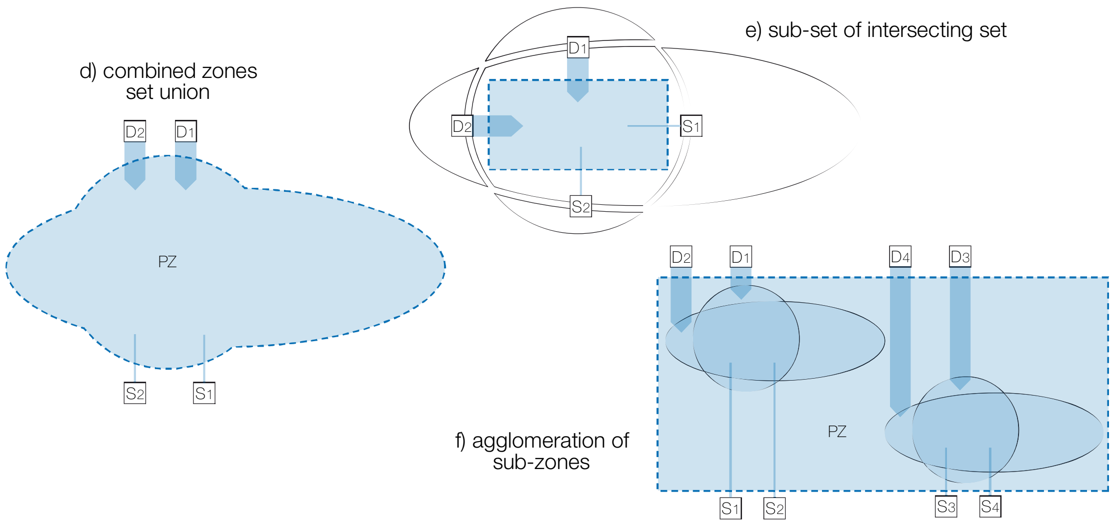


Figure 2.11 – physical zone configurations 2

The zone concept allows physical zones to be linked with each other via their ports. This feature makes the definition of the PZ very robust with respect to decomposition into smaller subsystems or aggregation to bigger system units.
For complex or large zone geometries showing considerably differing internal characteristics or constraints, zones can be split into any number of smaller interrelated subsystems.

In a wider sense and not in mathematical terms, the physical zone element can be compared to a simplified finite element description method for effect links within an architectural space configuration (Wong and Mahdavi 2000). Figure 2.12 shows the described splitting into smaller subsystems.

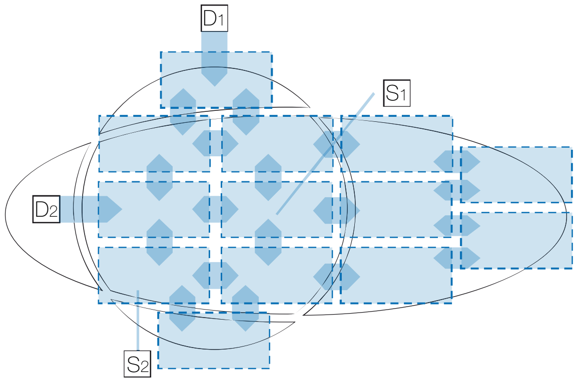


Figure 2.12 – physical zone configuration 3

Concluding, a physical zone corresponds to a 2- or 3D sphere as subset, intersecting set, union set or agglomeration of device zones. Within that PZ sphere it maps physical effects induced by devices. At this point, such a zone is not yet linked to architectural entities.

Physical zone – impacts and relations

The physical zone (see figure 2.13) can be viewed as a module, manipulated by several controlling devices via (input-) ports. Within the physical zone the primary and secondary effects of the control actions are effect-wise linked to the PZ's state space and made available at the system state terminals.

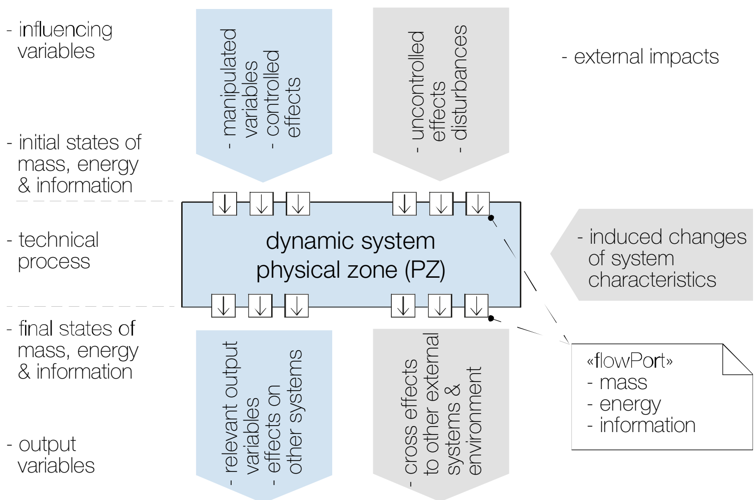


Figure 2.13 – physical zone, impacts and relations

The physical zone is also subject to disturbances as occupancy effects (number of persons, their activity) or climatic conditions (external climate, irradiation, wind, …).

The physical zone is the base element of the modular zone construction kit as used in this thesis. It is the pivot point for the device modules and for the access to the system states.

Primary- and secondary effects

Most device induced effects consist of a primary effect (intended effect) as e.g. illuminance induced by a lamp and secondary effects as e.g. the temperature rise due to the introduced thermal energy by the lamp.
A physical zone is not only affected by the contained several overlapping device zones but also by other physical zones. Figure 2.14 shows the primary- and secondary effects of a typical physical zone.

Input ports \ Output ports	energy	heating energy	irradiation	illumination	air	air temperature	air humidity	air quality
energy	S_2	S_2				P	S_1	
heating energy	S_2	S_2				P	S_1	
irradiation	S_2	S_2	P	P		S1	S_2	
illumination				P				
air		S_1			P	P	P	P
air temperature						P		
air humidity							P	
air quality								P
humidity							P	

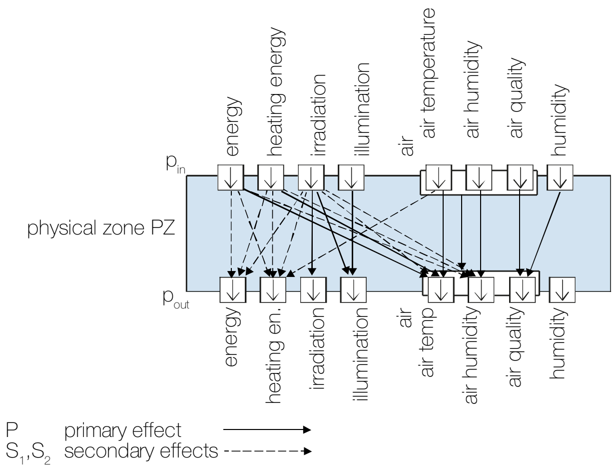


Figure 2.14 – physical zone, connections

Physical zone as single- and multiparameter systems

The minimal setting of a physical zone is represented by a system description with a single device effecting changes on only one state of the physical zone (primary effect only). Such a system is referred to a single input/single output system (SISO systems). This setting is presented in figure 2.15a.

In building physics, however, there are usually secondary effects associated with the desired primary effect. Such secondary effects imply changes of other system states than the primary controlled variable state, leading to a single-input/multiple-output system (SIMO systems). This situation is shown in figure 2.15b.

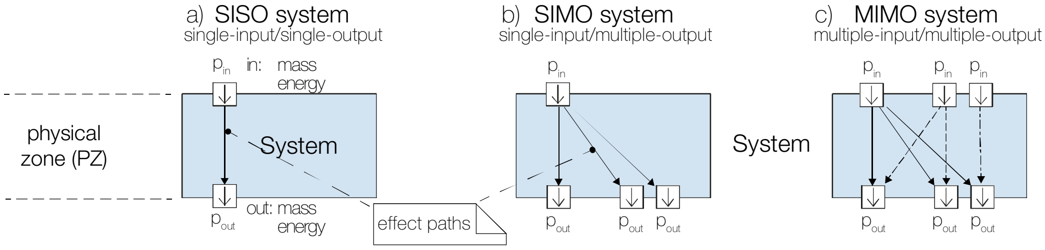


Figure 2.15 – SISO, SIMO and MIMO systems

Practical building control typically deals with physical zones affected by several devices with overlapping impact spheres (device zones). With overlapping device zones, PZ thus involve multiple device actions. Each of them causes primary and secondary effects and affect multiple states of the physical zone. Such systems are referred to as multiple input/multiple output systems (MIMO systems).

Physical zone -base module

The physical zone is the base element of the modular zone construction kit. It is the pivot point for the device modules and for the access to the system states.
To facilitate the system mapping in a simple way as shown in figure 2.3, the PZ modules incorporate a set of predefined ports and terminals (see figure 2.16) as well as predefined effect paths for primary and secondary effects (see figure 2.17).

The multitude of prewired but potentially unused ports/terminals and effect paths does not add to the final complexity (see chapter 3.5.1). Any unused ports, terminals or effect paths are eliminated in the course of the overall process. Figure 2.16 shows the predefined ports and terminals of the base module.

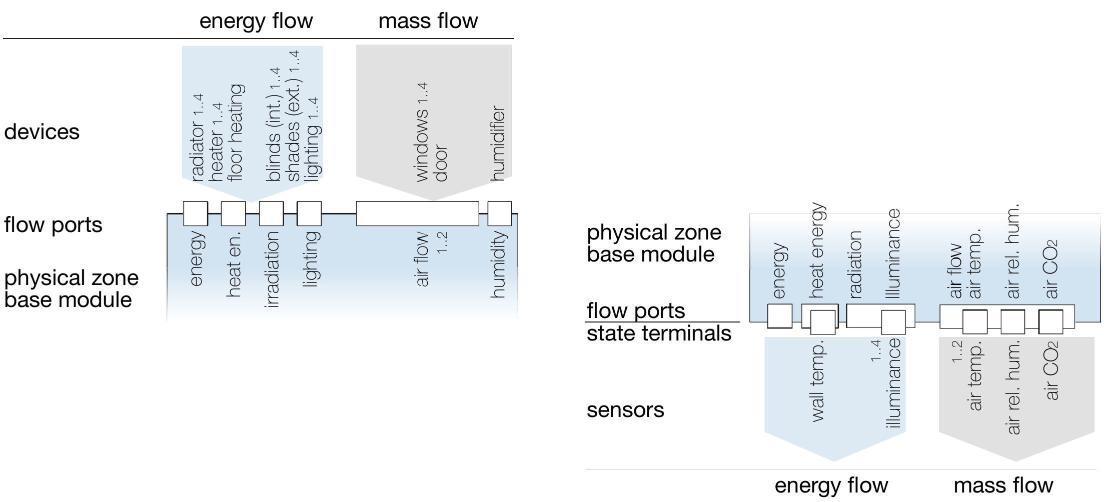


Figure 2.16 – physical zone module, ports and terminals

The reason for setting the cause-effect relation within the PZ-module is the conversion of the relational setup to a matrix representation. The predefined relations guide the user by proposing a set of common effect paths. Furthermore, it allows a simple straightforward linking process with the devices acting on the physical zones. The physical zone not only models the internal physical dependencies but also provides the necessary ports to map physical interactions of zones among each other.

Additional effect paths can be added to the matrix description of the physical zone or can be added to the system mapping in the form of units (see chapter 2.1.5).

Presentation as Graph- or Matrix

Graph description

Figure 2.17 shows another way to represent the relations between system inputs (control device ports) and outputs (ports and system state terminals) in form of a graph. Each system input port and output port/terminals are represented by a graph vertex. The connecting lines/edges between the vertices define a physical relationship. The causality relation is represented by a directed graph (see figure 2.18). The mapped physical effects have a defined direction, in this case from the input port to the output port (from top to bottom).

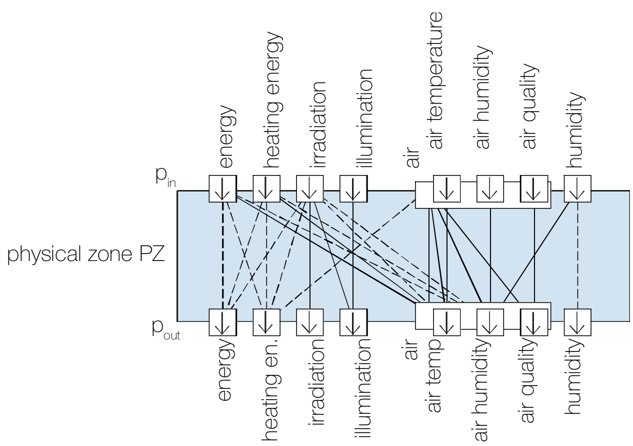


Figure 2.17 – physical zone, input-/output relations

Figure 2.18 shows the relations in a table- and a graph view.

A graphical representation is convenient for the visualization of system relations; however, it is not suitable for manipulating complex graphs or for computer algorithms.

Matrix description

The physical relationship of the graph can also be described mathematically in the form of a matrix, referred to as adjacency matrix; the input and output nodes are assigned to the rows and columns, non-zero elements indicate a presence of a connection. The elements can also store a weight, in the case of the physical zone the values correspond to the estimates for effect attenuation between input and output (0<f≤1).

The causality relation translates into a non-symmetric adjacency matrix (see figure 2.18 with non-weighed graph edges).

Input ports \ Output ports	energy	heating energy	irradiation	illumination	air	air temperature	air humidity	air quality
energy	S_2	S_2			P	S_1		
heating energy	S_2	S_2		P	S_1			
irradiation	S_2	S_2	P	P		S_1	S_2	
illumination				P				
air		S_1			P	P	P	P
air temperature						P		
air humidity							P	
air quality								P
humidity							P	

Adjacency Matrix

energy	heating energy	irradiation	illumination	air	air temp.	air humidity	air quality	humidity
1	1			1	1			
1	1		1	1				
1	1	1	1		1	1		
			1					
	1			1	1	1	1	
					1			
						1		
							1	
						1		1

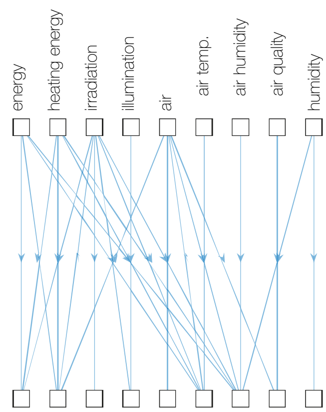


Figure 2.18 – physical zone, graph and matrix description

The matrix representation is very useful as it links graph theory and matrix algebra. A description using adjacency matrices allow graph manipulations by operating within the algebraic space of matrices. Matrices facilitate computation operations and aggregations of complex underlying systems and thus enables a scalable system approach.

2.1.3 Zone concept – context with building geometry

A declared objective is to embed the project process in established data structures, in this case into the IFC data structure used in the BIM concept. It is therefore necessary to verify whether a link between the effect-based zone concept and the spatial and geometric oriented structure of the IFC data can be established; and whether zones can be associated with parts, units or aggregations of architectural spaces (Mahdavi et al. 2015).

Physical zone - effect- or geometry-based

Physical zones (as device zones) are primarily linked to the characteristics and induced effects of controlling devices. As described before, the zone concept does not imply that the impact area of a device follows the shape of architectural geometries or spatial entities as spaces or rooms.

Architectural workflows however are mostly centered around 2D- or 3D-description of building geometries. Establishing a link between the effect-based spheres of physical- or device zones and geometrical boundaries would allow to relate the zone concept to architectural workflows and their geometry-based data structures.

Geometry-type building elements, also affect the virtual extent of the device zones. In general, such elements represent discontinuities for the propagation of device induced effects (e.g. opaque wall in case of light transmission). Such objects constitute discontinuities to the propagation of effects induced by devices (e.g. opaque wall for light transmission). Such discontinuities do represent a set of limiting boundaries, putting geometric limits to an effect-based impact sphere.

To analyze to what degree a link of the effect-based extent of the impact sphere with a geometric boundary can be established, the effect's primary propagation mechanism needs to be considered:

Propagation by radiation

With a given device characteristic, e.g. the photometric polar diagram of a lamp, the sphere can be easily calculated (see figure 2.21). For effect propagation by radiation the impact area can be imagined to be delimited by an iso-effect surface of a selectable limitational magnitude (0 ≤ lower limit value ≤ effect magnitude ≤ max. caused effect at the device). However, the limiting value (e.g. level of radiant flux or illuminance) can be chosen arbitrarily without questioning the underlying effect-based concept of a device zone. Lowering the limit values for the boundary definition will increase the virtual extent of the effect-based two- or three-dimensional impact sphere.

Depending on the arbitrarily chosen limit value, geometric boundaries can become active before/instead of the effect-based boundary by the iso-effect surface. Figure 2.20 shows an example configuration with active geometric boundaries.

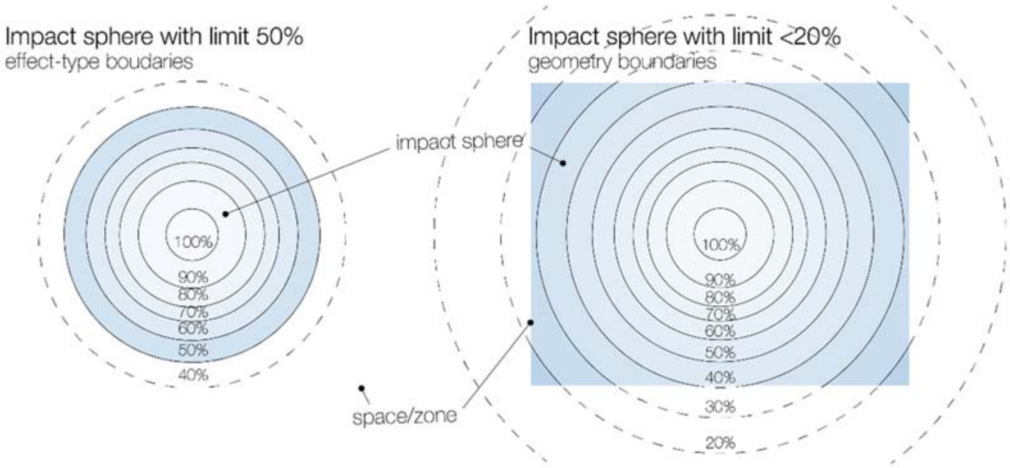


Figure 2.19 – impact sphere and limit definition

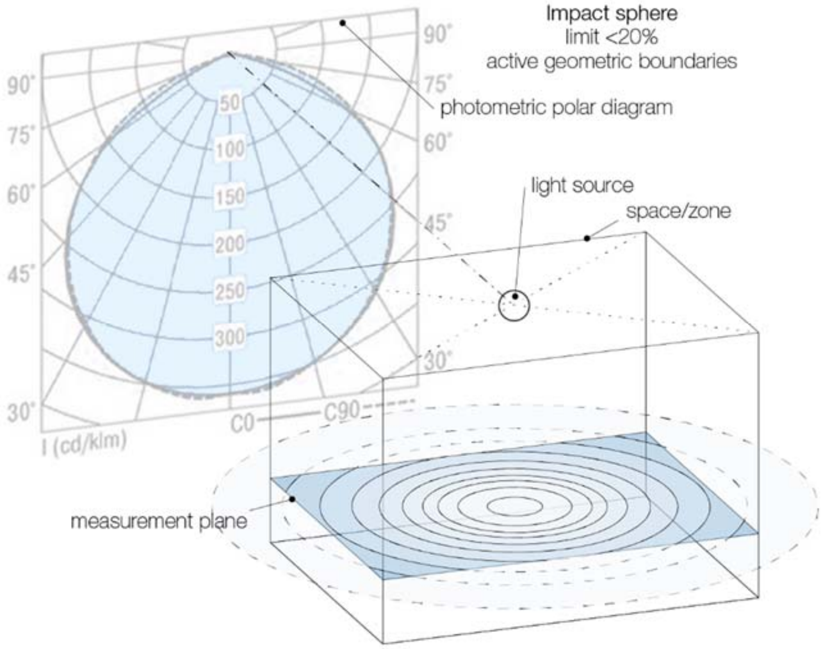


Figure 2.20 – impact sphere

In such cases the PZ configuration results in a subset of overlapping device zones as depicted in figure 2.21.

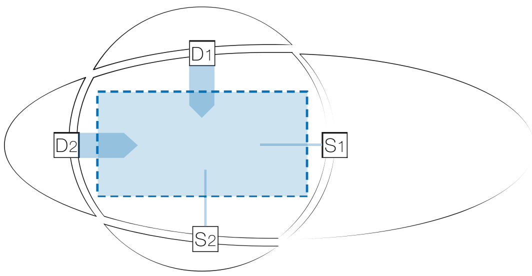


Figure 2.21 - physical zone, geometry limits

Propagation by fluid transfer (convection)

The task of defining the influence sphere of devices gets more complex once the device induced effect is propagated by the displacement of fluid (e.g. air). Thermal transmission effects like convection or ventilation cannot be derived intuitively and are difficult to calculate and need simulation in CFD (computerized fluid dynamics). Complexity increases as these spheres, delimited by iso-effect surfaces, do not necessarily form a convex area. Furthermore, they change their shape and size over time. Therefore, delimiting the impact area by arbitrary threshold values will not give a simple definable or delimitable 3-dimensional volume (see figure 2.22).
The assessment, calculations and simulations of fluid dynamics do require a complete set of boundary conditions, especially the indispensable geometry boundaries. Hence, for effect propagation based on mass transfer (e.g. convection, ventilation) there is a mandatory link into geometric boundaries.

Figure 2.22 – propagation by convection (Österberg 2011)

Simultaneous propagation modes

Some devices act on their environment based on more than one physical transmission effects. These can show different modes of effect propagation, leading to different spheres of influence. E.g. a room heater displays both a radiant and convection effect; the more definable radiant part, and the convection part showing above described fluid dynamics impact.

Other effects

Geometric boundary conditions not only cause propagation discontinuities by changing the intensity of the transfer effect but can also cause reflection effects. Such effects manifest another link between the effect- and geometry-based concept of the active zone.

Effect-based vs. geometry-based - summary

The zone concept describes the areas of intended impact (device zones) and the derived aggregations (physical zones) as spheres being independent from shape or geometry of architectural entities. The typical impact area and the extent of the device zone is initially only influenced by characteristics of the device and the underlying physical propagation effect.

As derived above, for radiant propagation effect a relation of the physical extent of a device zone and the geometry of spaces can be derived via propagation discontinuities. To derive the extent of impact spheres for propagation effects involving fluid dynamics, geometric boundary conditions are mandatory. This situation by definition links the effect-based zones with geometrical boundaries.

Thus, even though the effect-based concept does initially not relate to building geometries, a relation between the extent of physical zones and the geometry of building spaces can be established or is even required.

2.1.4 Control zone (CZ)

A control zone level is introduced in order to establish the first controlled level within a hierarchical and coordinating control structure. In terms of control circuits, it represents the controlled system to the zone controller (ZC).
The control zone combines the lowest level of controlling elements (device controllers, devices) and one controlled system (physical zone as aggregation of device zones). Figure 2.23 depicts the structural sequence of device zone – physical zone – control zone. The control zone is in general related to geometry-based zone boundaries.

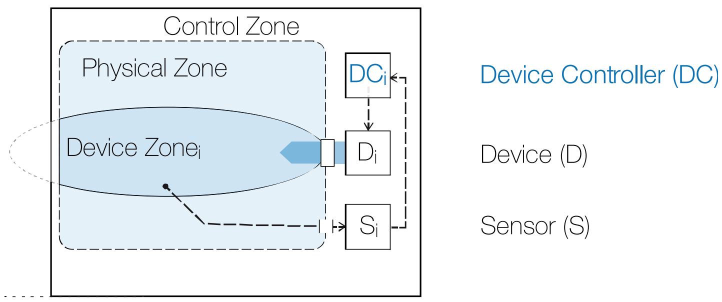


Figure 2.23 - control zone

2.1.5 Units (U) and Elements (E) as special constructs

As described, the physical zone is the base element of the modular zone construction kit. It provides a set of predefined ports and terminals as well as their related effect paths (see figure 2.17). Users can easily select the devices and sensors by choosing from provided related ports and terminals.
The modules predefined effect paths relate the primary and secondary effects of the selected devices to the respective system states. Selecting components from a list facilitates a straightforward system mapping approach. The multitude of prewired effect paths for different devices does not add to the complexity for the mapping process (see chapter 3.5.1) as the unused connections are automatically eliminated in the course of the overall process.

However, not to overload the predefined functionality of a physical zone module, some special cases are mapped by using other constructs, the physical 'units'.

Completing the 'zone' concept, the ‘unit’ concept describes encapsulated systems (e.g. HVAC systems) or systems with very specific functionality. They are modelled as abstract zones and can be implemented within the presented zone concept. The out-ports (mass or energy) of such systems are linked to the input ports of one or more physical zones. Higher-level building control can act on these virtual zone systems by transmitting target values.
Examples of such units are:

- Systems, incorporating themselves a complex self-contained control system as HVAC systems
- Devices influencing more than one physical zone as e.g. an outside shade or louver system, spanning the same setting across several windows or a bigger area of the buildings envelope, thus influencing several physical zones.
  Such devices are mapped as self-contained zones. They can contain a controller for e.g. the shades position. The out-ports of such 'special zones' are linked in a 1:n relation to the input ports of the affected physical zones.

2.2 Spatial structure

Decomposing bigger structures to manageable substructures is the principle approach for the structural system mapping process. This not only stands for the discussed zone concept, but also applies to breaking down big and complex building structures into smaller architectural entities.

The spatial decomposition process extracts the necessary geometry and spatial data from the IFC building data model.

The IFC structure and the described spatial elements is structured hierarchically. The spatial hierarchy – building-storeys-space – corresponds to the hierarchical composition of building objects in the IFC - Industry Foundation Classes (buildingSMART 2018).

Spaces can be seen as the equivalent to a physical/control zone; but can also comprise several physical zones or relate into a bigger aggregated physical zone.

IFC spatial structure hierarchy

An IFC spatial model is composed of IFC entities, organized in a hierarchical order (see figure 2.24).

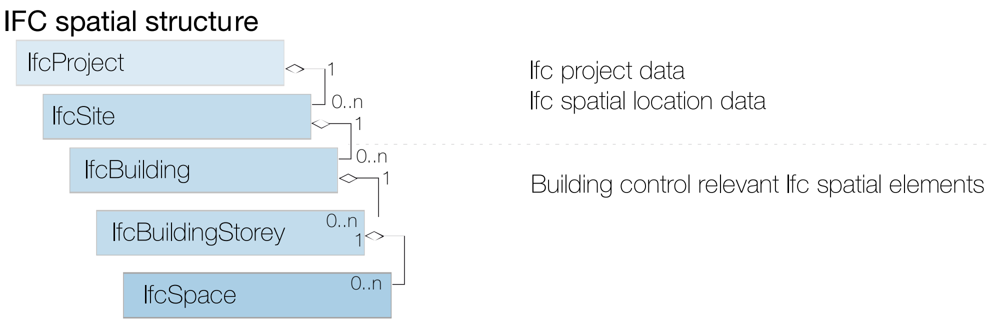


Figure 2.24 – IFC spatial structure hierarchy

The principle and relevant elements for the spatial data model are listed below, the definitions are following (buildingSMART 2018):

- **IfcSpatialStructureElement**
  A spatial structure element (IfcSpatialStructureElement) is the generalization of all spatial elements used to define a spatial structure. That spatial structure is often used to structure and organize a building project.
- **IfcProject**
  The IfcProject establishes the context for information exchange with the main purpose to provide the root instance and the context for all other information

items included such as default unit assignment, geometric representation context and world coordinate system.

- **IfcSite**
  IfcSite positions and references the IFC data set with an absolute placement in relation to the real world.
- **IfcBuilding**
  A building or a collection of buildings is associated with a site. A building can also be decomposed in parts, where each part defines a building storey or section.
- **IfcStorey**
  The building storey typically represents a horizontal aggregation of spaces. Building spaces, however, can also be aggregated in vertical parts, where each part defines a building section. As the spatial hierarchy decomposition for the system mapping is not limited to a horizontal aggregation direction, e.g. in case of vertical zoning (Mahdavi et al. 1998). The term IfcStorey in this context is thus used to refer to a horizontal and/or vertical section of a building, leaning more towards the term 'area' as defined in VDI3813 (VDI 8313).
- **IfcSpace**
  A space represents an area or volume bounded actually or theoretically. Spaces are areas or volumes that provide for certain functions within a building (buildingSMART 2018). The IFC-structure also provides for further division and a space can also be decomposed in partial spaces.

Subspaces

The concept of a physical/control zone does not necessarily form a one-to-one relation with architectural spaces as rooms as represented by IfcSpaces.

Spaces can be seen as the equivalent to a physical/control zone; but can also comprise several physical zones or relate into a bigger aggregated physical zone.

Depending on the device zone characteristics and/or the size and shape of rooms more than one physical zone can be assigned to a single space/room. In this case the zone represents the physical system within a partial space. A zone can also refer to bigger physical zone as aggregation of several architectural spaces.

The IFC-structure does provide elements with similar names to the zone concept – the IfcZone and IfcSpatialZone – but these do not translate directly into the representation of a physical zone.

- **IfcZone**
  An IfcZone is a spatial system, grouping individual IfcSpace's (and other IfcZone's). However, an IfcZone does not represent an own geometric representation
- **IfcSpatialZone**
  A spatial zone is used for a functional and not hierarchical decomposition. Spatial zones can be used to represent a thermal zone, a construction zone, a lighting zone, a usable area zone. This would qualify the IfcSpatialZone element as the counterpart of a physical zone, however it is a potentially overlapping element with independent placement and shape representation.

Figure 2.25 shows the relation of the hierarchical spatial structure (IFC data structure) and the zone concept. The building complex is broken down to the IfcSpace-level. Within that framework the zone elements - from the device zones up to the physical- and control zone - serve as the first elements of the bottom up aggregation of the hierarchical control system.

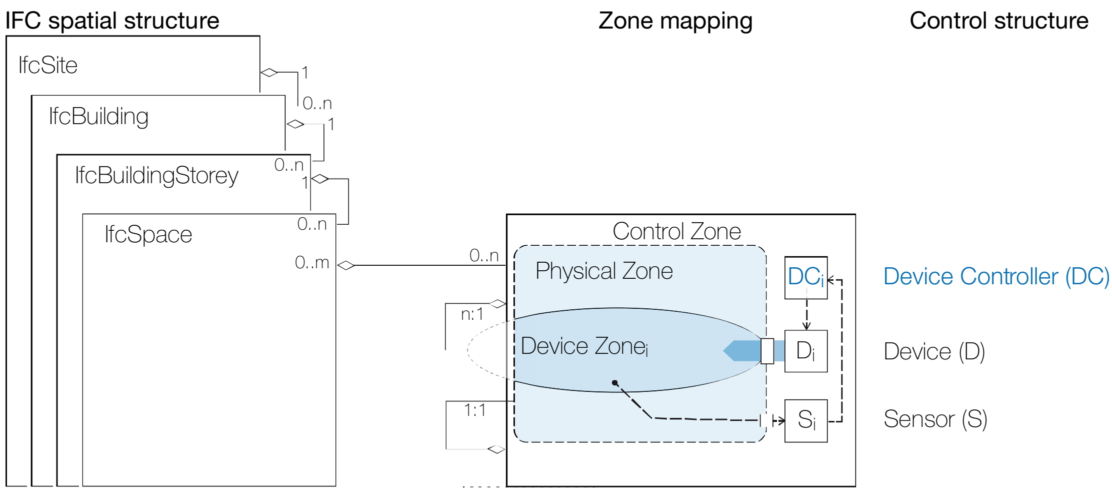


Figure 2.25 - IFC spatial structure, zones and control structure

2.3 Control – structure & hierarchy

In this section, the system elements acting on a controlled element (physical zone) are reviewed in more detail from a classical control theory (closed-loop control) point of view. Basic control circuits are based on modular control elements. Simple single-input/single output systems are aggregated to a multi-parameter hierarchical control concept and established control structures for the control of such MIMO systems are examined.

The control structure is compared to standard hierarchical feedback control structures as well as to related strategies in automation engineering.

2.3.1 Control

Building control systems

In terms of classical control theory, a building and its systems represent a dynamic multivariant controlled system with partially nonlinear characteristics of its subsystems.
The building's controlled system is significantly impacted by environmental (climatic conditions, irradiation) and occupancy induced disturbance parameters. Occupancy number and activity level are direct impacts to the controlled system; but occupants also indirectly influence the system by defining the target setting of comfort parameters, as thermal-, visual comfort and indoor air quality.

Another building specific system behavior relates to a generally slow response characteristic compared to the dynamic of the disturbance variables. On the other hand, this fact entails potential energy savings when using the buildings thermal mass as intermediate energy storage to reduce and shift the peak energy demand (Xu 2010).

An integrated approach to building controls, needs to consider the multivariant characteristics of the subsystems (MIMO) and interactions between them. The control system structure has to be robust with respect to changing dynamic parameters, interrelation effects and operational characteristics (Kim et al. 2012).

Control elements & circuits

The used terms follow the IEC 60050-351 (IEC 2014). The control groups and elements of basic control system are depicted in figure 2.26).

Control circuits

Control systems are a central part of automation with the objective to attain and/or maintain a targeted system condition despite any occurring disturbances (e.g. external conditions, occupancy interference, …).

There are two principal control structures:

- the **open-loop or feed-forward control** (see figure 2.27)
  In an open-loop control, the control actions affecting the system are set independently and without measuring the actual controlled process variable, thus without information whether or to what degree a targeted result has been achieved.
- the **closed-loop or feedback control** (see figures 2.26 and 2.27)
  closed-loop control is a process to reach or to maintain a desired system condition; this is achieved by continuously comparing the controlled process output parameter with a command- or reference value.

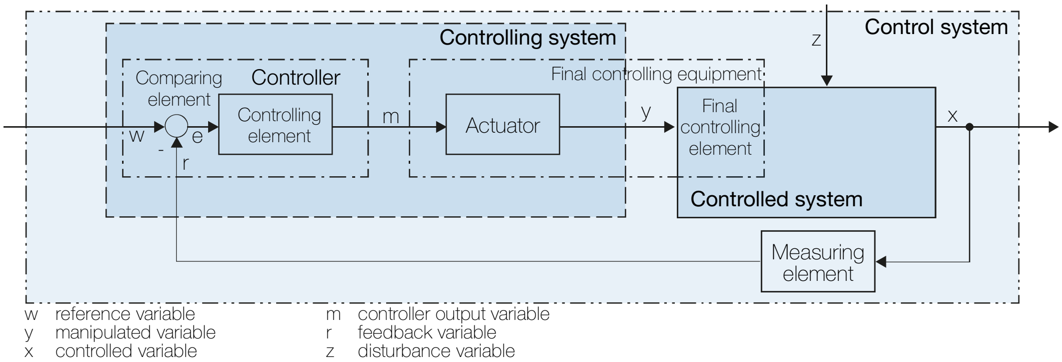


Figure 2.26 – closed-loop control circuit (DIN IEC 60050-351)

The standard DIN IEC 60050-351 (DIN IEC 60050-351) defines feedback control as: “closed-loop control or feedback control, a process whereby one variable quantity, namely the controlled variable is continuously or sequentially measured, compared with another variable quantity, namely the reference variable, and influenced in such a manner as to adjust to the reference variable”.

Control actions are reactions to a deviation of the control variable from its targeted value, hence classical closed-loop control strategies can be categorized as a reactive process. Other, more advanced control strategies, as simulation- or model-based control strategies (see chapter 2.3.6) are considered to be proactive processes.

Basic control systems – elements & parameters

Open-loop control

In an open-loop control, the control actions affecting the system are set independently and without measuring the actual controlled process variable, thus without information whether or to what degree a targeted result has been achieved.

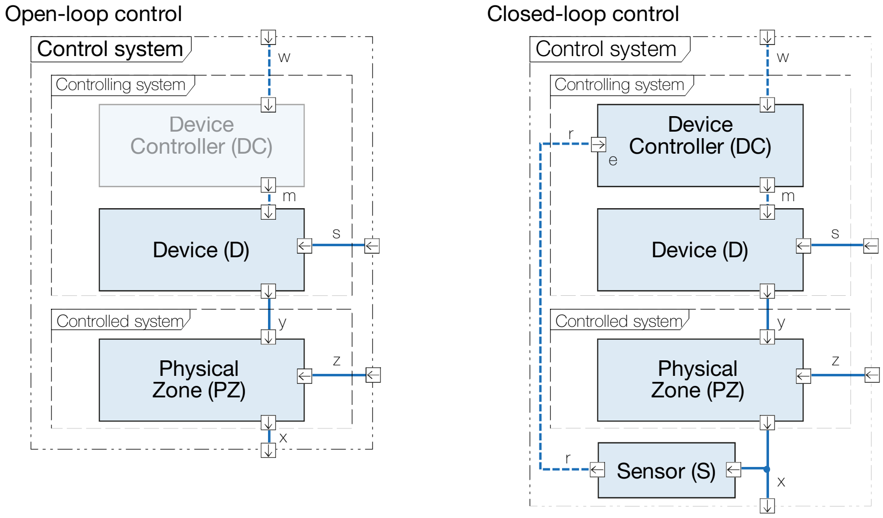


Figure 2.27 – open- and closed loop control

A minimum configuration of an open-loop control system consists of:

- Controlled system:
  - Physical zone
- Controlling system:
  - Actuator
  - Device (including the final control equipment)

For the previously discussed zone concept such a minimum open-loop control system consists of an actuator and/or device acting via the device zone on a physical zone.
In case of manual operation there is no device controller, e.g. if the actuator as element within the controlling equipment (actuator and final controlling element – device) is operated manually/externally. The primary (and secondary) effects linked to a specific device type result in state changes of the respective controlled variable or PZ's output parameter.

Closed-loop control

The control objective in technical processes is to maintain one or more output parameters (controlled variables) of the controlled physical system within specified limits. This, over time and under the impact of disturbance variables on the physical system. To meet these objectives, the respective output values of the physical systems are measured and compared with the target value. The controller continuously adjusts the controller output variable, based on the computed offset between the target value and the actual measured output value (controlled variable).

Figure 2.28 shows the basic elements of a closed loop control system based on to DIN IEC 60050-351, modified for the applied component names in this thesis (e.g. the 'device' component).

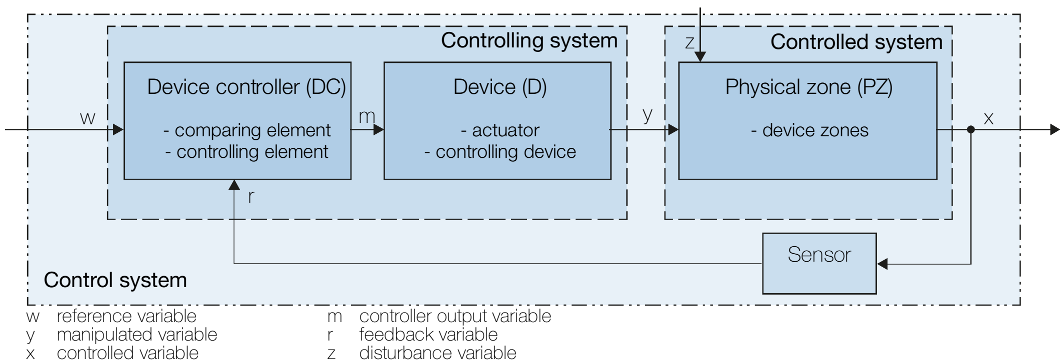


Figure 2.28 – control circuit, modified device interfaces

A base configuration of a closed-loop control system consists of:

- Controlled system – Physical zone (PZ).
  The controlled system reflects the dynamic relations between the input parameter (manipulated variable) and the controlled variable(s).
  The controlled system directly corresponds to the previously described physical zone (PZ) of the zone concept.

- Controlling system – Controlling Device (D)
  The controlling equipment directly correlates with the concept of the device controller (DC) and the controlling device, or 'device' (D).

- Measurement element - Sensor (S)
  The measurement unit or sensor (S) accesses the state of the controlled variable and provides the information type feedback variable. In this work it is assumed that a sensor information is made available throughout the building automation network,

hence to all controllers requiring information on a specific output state.

Sensors also can establish non-accessible, estimated or virtual system information by computation from accessible parameter values and/or knowledge of systems dynamics (e.g. state observers).

Representation of control structure/circuits

From this point onwards the well-known horizontal depiction of a control system, as discussed in chapter 2.3, will be presented in a vertical form, as shown in figure 2.29.

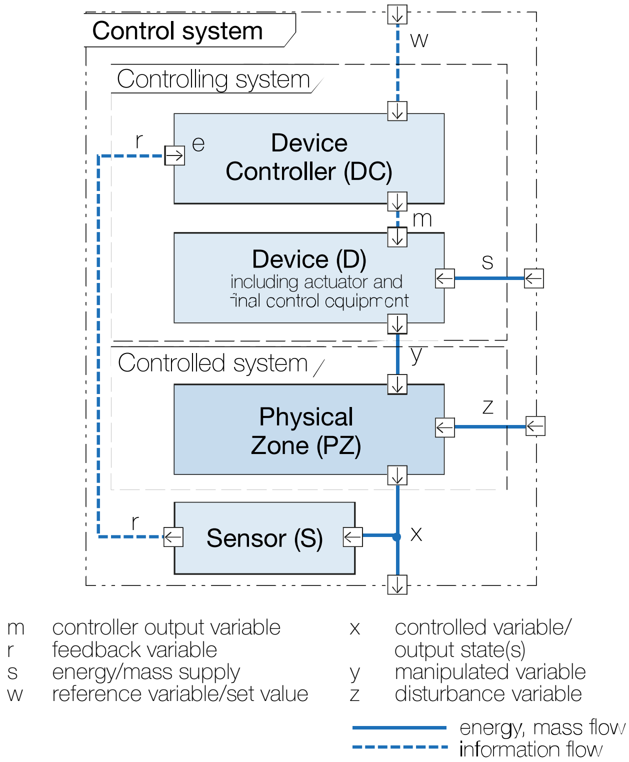


Figure 2.29 - closed loop control circuit

The reason for this arrangement is that for hierarchical system considerations a vertical representation is more consistent with the concept of hierarchical control and control structure; and it is easier expandable to several hierarchical levels.

2.3.2 Single- & multi-parameter control systems

Controlled system

When looking at the effect paths or transfer function of a controlled system, these systems can be categorized by the number of input variables and the number of the respectively affected output parameters (see figure 2.30).

As discussed before, most device actions entail primary- and secondary effects, characterizing them as SIMO controlled systems (single-input/multiple-output systems). This is the standard model describing device zones.

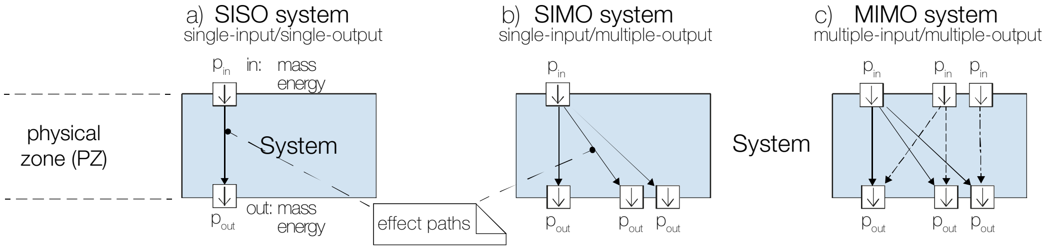


Figure 2.30 - SISO, SIMO to MIMO system

Building control typically involves physical zones affected by several devices with overlapping impact spheres (device zones). The PZ's are thus modelled as system blocks with multiple inputs (device control ports, manipulated variables). Such systems as aggregations of SIMO systems, are referred to as multiple input/multiple output systems (MIMO systems) (Fradkov et al. 1999).

Control of SISO, SIMO and MIMO systems

SISO-systems

Basic forms of controlled systems have one input variable (manipulated variable) and one output variable (controlled variable).

In a simple control circuit, the controlling equipment (controller and respective controlling device) acts on a single input parameter of the controlled system. In a SISO controlled systems only one output parameter is affected. Such systems are referred to as single-input/single output systems or SISO systems. The figures 2.26 to 2.28 and 2.30a refer to such SISO control systems.
Measured by the sensor, the actual state of this output variable, the controlled variable, is fed back to the controller (see figure 2.29).

SIMO systems

For SIMO systems a change of a single input parameter of the controlled system affects multiple output states. The system response regards at least one output relating to the primary effect and other output changes caused by secondary effects. The sensor signal for the closed-loop control is usually taken from the system output variable related to the primary effect.

Figure 2.31 shows control circuits for SISO, SIMO and MIMO systems.

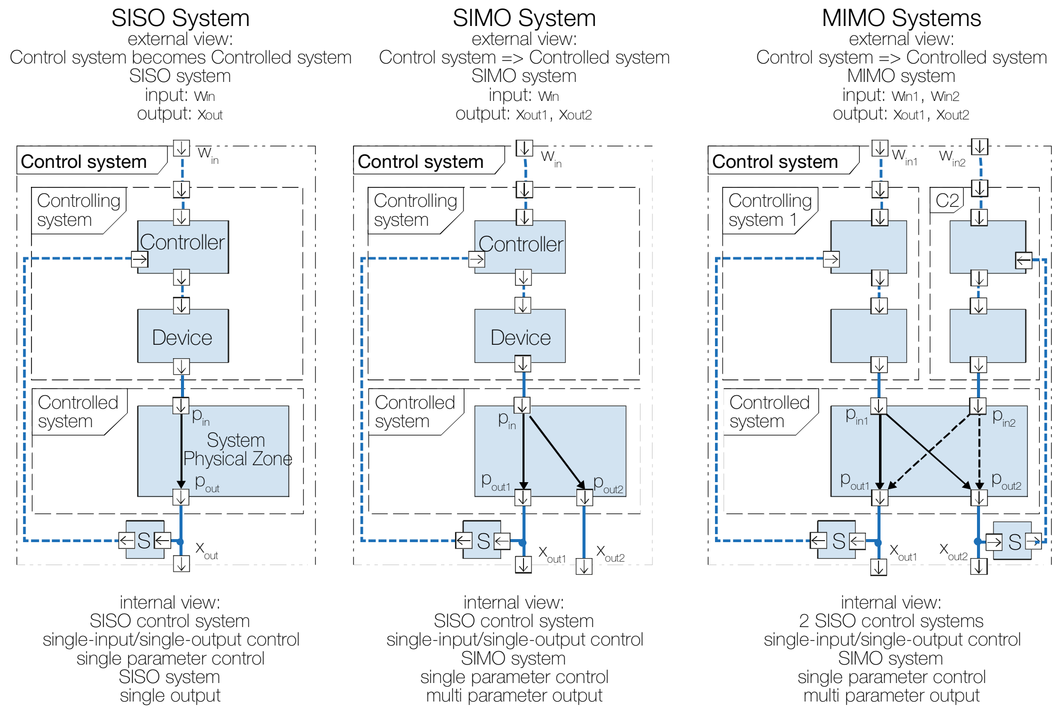


Figure 2.31 – SISO, SIMO and MIMO system control

Control of MIMO systems

The control of building systems typically involves the simultaneous control of multiple and often interacting/interrelated parameters. The change of one actuating variable effectuates changes of more than one system output parameters, and in some cases more than one controlled variable (see figure 2.30).

2.3.3 Multi-parameter control

The control of MIMO systems is more complex than controlling specific outputs in a single parameter control loop.

Multi-parameter control systems manage multiple control parameters of a coupled MIMO system simultaneously. Examples for multi-parameter control of MIMO systems are air-conditioning control systems, controlling the strongly coupled parameters ‘temperature’ and ‘humidity’, or ventilation with linked effects on temperature, humidity and CO_2 level.

Building's controlled systems consist of a high number of physical zones and their interrelations and tend to become very complex. Due to the involved system complexity and scalability issues it is not practical to create one centralized building control in a form of a monolithic control system. Such centralized control is also not suitable for integration of additional BACS tasks beyond performing control as e.g. complex optimization processes with multiple target settings (situation context, optimization targets) to simultaneously achieve optimal comfort criteria, energy savings, and optimize economical parameters.

Building control involves a multitude of MIMO systems and results in structural complexity. Such structures can be managed with different concepts, depending on the structural and dynamic characteristics (e.g. degree of coupling).

Decentralized control

In case of weak parameter interrelations, the multi-parameter control system can be split into a set of independent SISO control systems, acting on their respective subsystems only (Knorn 2011). Figure 2.32 shows the structure of a decentralized control vs. a centralized control strategy, figure 2.33 shows the control related view.

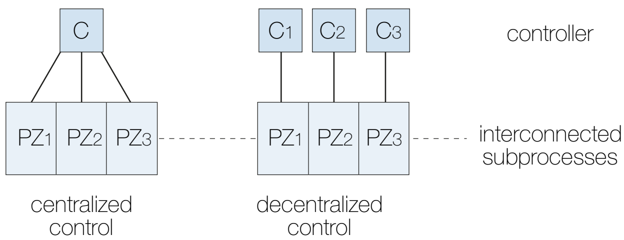


Figure 2.32 – centralized vs. decentralized control

The concept of decentralized control is based on the decomposition techniques of complex systems, where a large-scale control problem is broken down to more manageable subsystems. These subsystems are then considered as independent and autonomous control systems. In this approach coupling effects to other subsystems are disregarded; as a consequence, the remaining coupling effects into other controlled SISO/SIMO systems are considered as disturbance variables.

Each SISO subsystem with one manipulated- and one controlled variable is controlled by a designated controller. Disturbances being coupled in from other subsystems are compensated by the controller. This method is widely used and provides reasonable results with weak coupling or with slow coupling effects compared to the main controlled system.

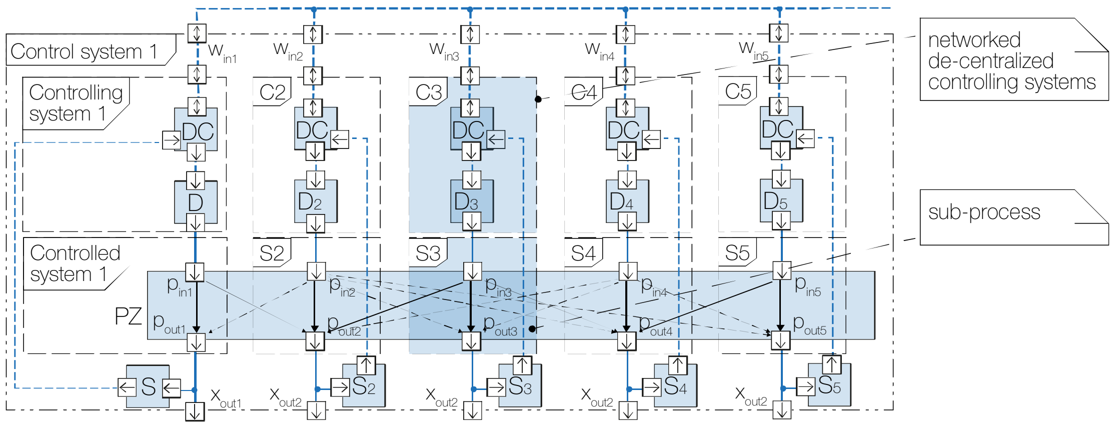


Figure 2.33 – decentralized control

In case the subsystem can be operated with only locally available information (system states/outputs) the implementation of such decentralized control of subsystems requires less communication with other subsystems, which has economic and reliability advantages (e.g. self-contained subsystem operation).

However, the compensation actions for coupling/disturbance effects can lead to dynamic perturbations (beats and instabilities) and to suboptimal performance with respect to the overall performance (e.g. energy consumption).

The subsystems are optimized with respect to sub-goals considering their respective tasks and requirements. There is no coordination in order to optimize or adapt the processes to meet higher-level optimization targets or overall goals.

Control with decoupling controller

The control of a MIMO system can be set up analog to control of single parameter systems.

The system consists of standard type closed-loop control circuits with a controller assigned for every controlled variable (C1, C2).

Added decoupling controllers compensate process interactions and the impact of other actuating variables on the respective controlled variable. Figure 2.34 shows a control circuit with decoupling controllers. For changes of one command/set variable (w), the decoupling control only affects a change of the one respective controlled variable.

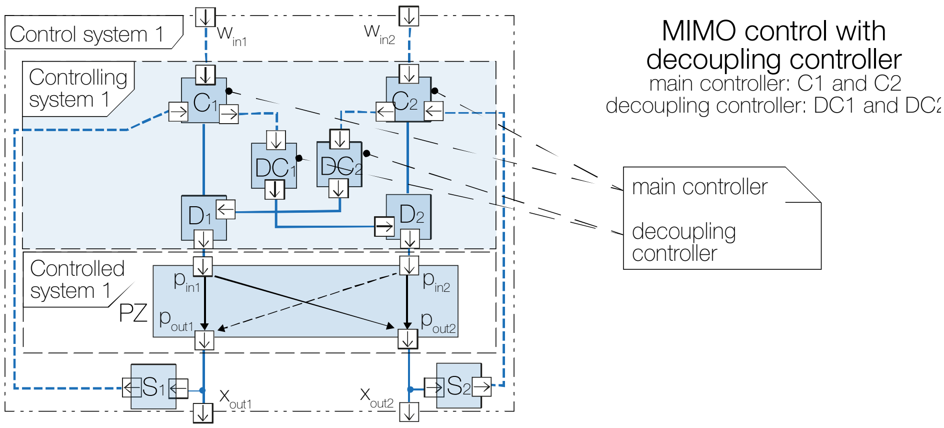


Figure 2.34 – MIMO control with decoupling controllers

In a building's high number of control circuits with interrelating effects, the system of decoupling controllers quickly gets too complex. The concept of decoupling controllers is hardly scalable to bigger systems as for complete buildings. Furthermore, it is not flexible in case of control system relevant adaptions or changes during the utilization phase of the building.

Genuine Multi-parameter Control

A multi-parameter controller has n inputs (n = number of controlled variables) and m outputs (m = number of manipulated variables). The coupling effects between the components are accounted for in the controller concept/algorithm. Some control strategies have an inherent multi-parameter control capability (e.g. Model Predictive Control algorithms).

The disadvantages for scalability and when dealing with large-scale and complex systems resemble the previously discussed (decoupling controller) approach.

Higher-level MIMO control

If genuine multi-parameter control is not applicable (controller complexity and robustness) a coordinating controlling algorithm can assign target values for individual SISO control circuits to decouple or minimize the cross effects. E.g. algorithms as Model Predictive Control (MPC) are suitable to limit unwanted cross effects by minimizing their predicted effect magnitude. Figure 2.35 shows the principle of a higher-level coordinating control.

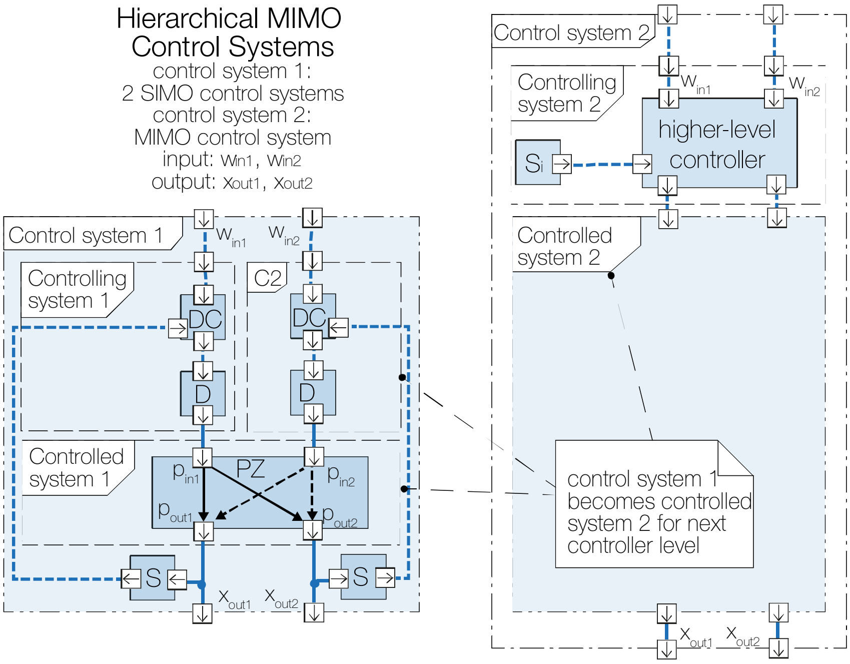


Figure 2.35 – hierarchical control

2.3.4 Multi-level control

Another approach to multi-parameter control of complex systems is to add higher level controls for the coordination of decentralized control cells.

Cascade control

Cascade control represents a hierarchical control system. It is not a control strategy for MIMO systems per se, but it displays some structural similarities to hierarchical multi-parameter control (see below).

Instead of using closed-loop control as one dynamic block, it can be useful to partition the controlled and controlling system into subsystems which are linked in series.

Cascade control is a closed loop control in which the output variable of one controller, the main or leading controller, is the reference variable of a secondary control loop (see figure 2.36).

The inner/secondary control is operating on the reference variable, provided by the main controller and with measurement and feedback of secondary controlled variables only DIN IEC 60050-351 (DIN IEC 60050-351:2006).

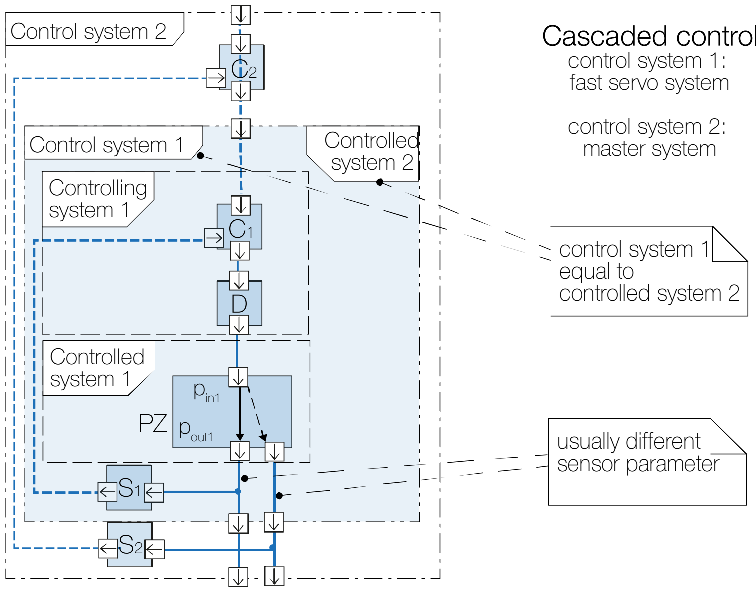


Figure 2.36 – cascaded control

A dynamically important aspect are the time constants of the stacked and interlaced control layers. The inner controller (C1) generally is designed for a faster dynamic response and relieves the outer controller of high dynamic responses.
The outer controller (C2) can operate on a less dynamic variable and/or has a longer response time to allow additional tasks (e.g. perform optimizations) or use more computationally intensive algorithms (e.g. model based control algorithms).

A dynamically significant faster inner control circuit results in a de facto separation of the two control processes and simpler configuration of the controllers (Schumacher and Maurer 2014).

In the context of hierarchical control systems, there are different notions of 'controlled system' boundaries involved. For a simple control circuit, the controlled system is as depicted in figure 2.38, whereas for the next control hierarchy level, the controlled system comprises the complete lower level control circuit. The higher-level controller output variable is the input for its controlled system; there it reflects the command variable (reference- or target variable) for the lower-level control circuit/controller (see figure 2.38).

Hierarchical control

For highly complex systems as building systems, it is in general not reasonable to develop a centralized control with one monolithic global controller but to develop a structure of coordinated decentralized control systems. A complex system decomposed into strongly related control subsystems can be coordinated in an added coordination level. Controllers at this coordinator layer manage the interrelations between the decentralized control subsystems and synchronize the sub-targets in order to attain an overall optimum.

DIN IEC 60050-351 (DIN IEC 60050-351) defines hierarchical control as a "functional structure of a control system with several control levels placed one over the other, in which controller assigned to a higher level coordinates the operation of the controllers assigned to the next lower level, providing for instance command variables, reference variables or final control variables". Figure 2.37 shows the concept of hierarchical control in context with centralized and decentralized control.

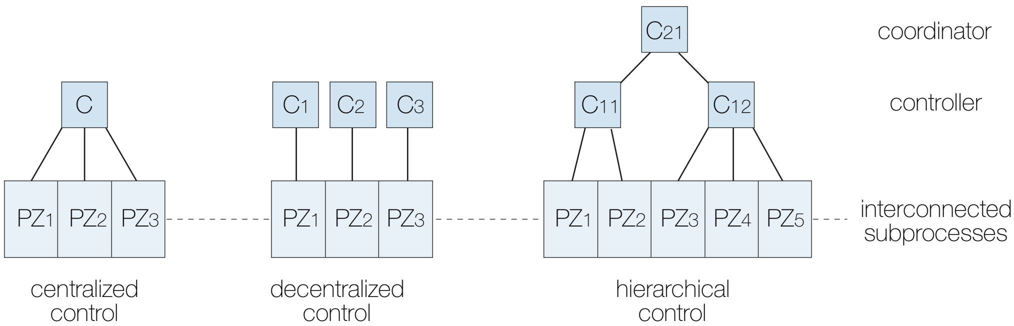


Figure 2.37 – centralized, decentralized and hierarchical control structure (DIN IEC 60050-351)

Hierarchical control combines a distributed control approach, higher-level MIMO control and a multi-level control as discussed in cascaded control. The hierarchical layer represents a coordination layer designed for cross segment control tasks.

The advantage for cascade control of relieving higher control levels from the need for fast dynamic response also applies to hierarchical control. As the required computer operations increase disproportionately with the increase of control system's complexity, this advantage can be decisive (Clemens 1993). The controller strategies in hierarchical layers can be optimized for response requirements (dynamic response) and/or different time horizons for predictive control strategies. (Hopfgarten n.d.).

Other than with the distributed control, the interrelations between the subsystems can be factored into the coordination strategies, the subsystems targets can be coordinated in view of a more holistic optimization process. Conflicts of objectives due to differing targets can be addressed in coordination layers of the hierarchical control structure by different strategies, e.g. rule-based or by more involved multi-parameter optimization.

The hierarchical control approach is flexible with respect to changes of the building spatial setup (zones) and provides scalability both in the necessary software modules as well as in the overall control structure.

Multi-level hierarchical control

Depending on the required coordination aspects, it can be necessary to organize a hierarchical system in form of a multi-level hierarchical control. Figure 2.38 shows a hierarchical control with 3 levels.

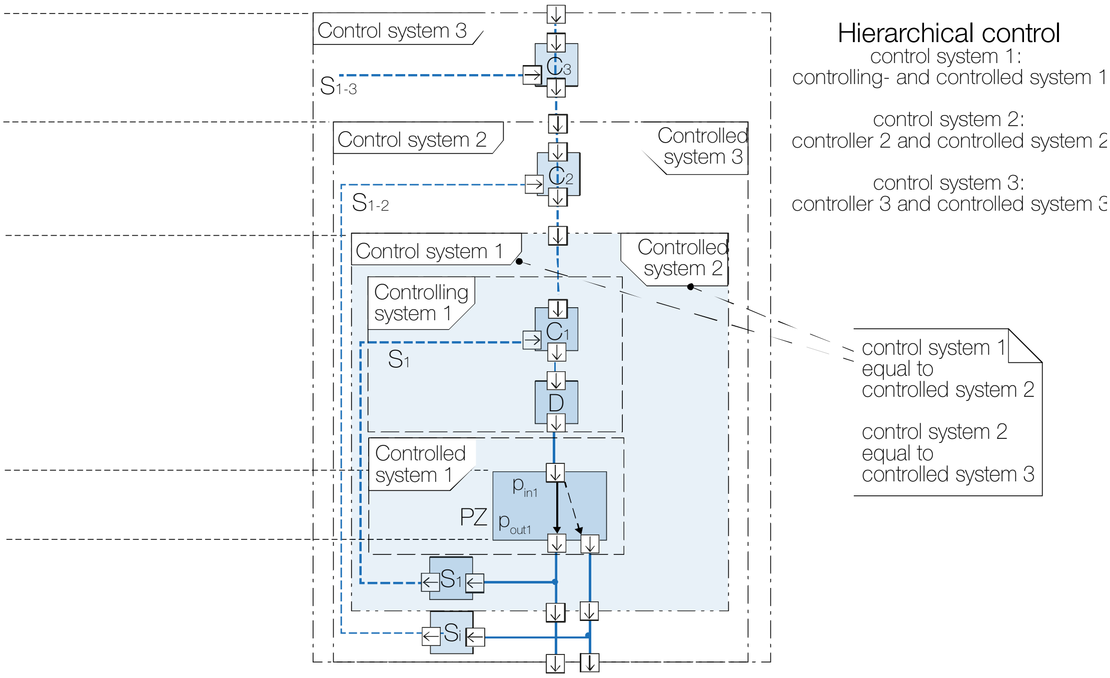


Figure 2.38 – multi-level hierarchical control

The lower control levels are responding fast within short reaction time to deviations of the controlled parameter or to disturbances. The higher hierarchical levels may react slower and therefore have computational capacity apart from coordination tasks. Such additional tasks are optimization processes with hierarchically differentiated target settings or computationally intensive algorithms. They span from decoupling control for lower coordinating levels up to energy supply/minimization and economical optimization tasks for the higher coordination levels.

Moreover, the respectively next hierarchical controller can provide fault mode functionality in case of malfunctions in lower controller levels, thus providing increased system robustness and support towards fault tolerant operation of the control system.
The level and task assignment is attributed depending on the actual control application. For the underlying building control scheme these layers are (also see chapter 3.7):

- **process level** <-> physical zone PZ
  represents the controlled physical process or in this case the concept of the physical zone PZ and devices assigned to the physical process are located to this level.
- **control level** <-> device controllers DC
  refers to the controllers directly acting on the actually controlled system PZ control.
- **coordination level 1** <-> zone controller ZC
  coordination of spatial level (e.g. several device controllers acting on one output)
- **coordination level 2** <-> high level controller HC
  coordination on functional level (e.g. several ZC acting on one DC controller)
- **supervision/management level** <-> meta controller MC
  other organizational processes, general optimization and coordination of process, fault diagnosis, etc.

2.3.5 Structural Representation

Adjacency matrix structure

The structural mapping of a system or hierarchy can be represented in the form of a directed graph and/or by the graph's adjacency matrix.
As the modular block scheme of the structure itself, the hierarchy representation within an adjacency matrix can be built in a modular manner. Figure 2.39 shows the internal structure of the adjacency matrix with the zone subsets on its diagonal.

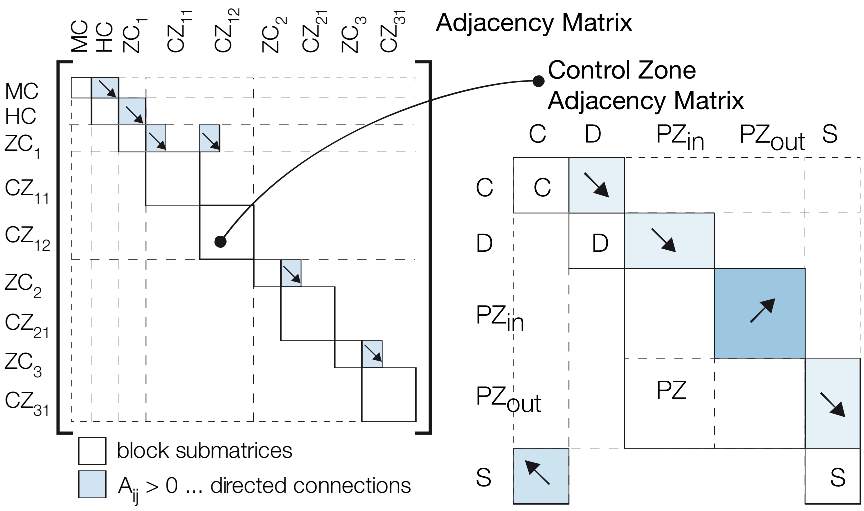


Figure 2.39 - Structure of adjacency matrix

Relations and effect paths within control zones are represented by submatrices within the overall system's adjacency matrix. Physical zones within a control zone hence are a further subset to these block matrices. Several control zones as well as coordinating higher controller levels can be aggregated and linked within the system's adjacency matrix. Links from elements or blocks figure to the right of these submatrices. Relations into blocks are arranged above these blocks.

Matrices represent a suitable method for scalable system descriptions, calculation algorithms and graph calculations.

2.3.6 Advanced control strategies

The most general objective of building control is to provide an optimal working or comfortable living environment. Especially for functional buildings, additional optimization in terms of energy demand, operational cost and efficiency are the dominant objectives. Big efforts are undertaken to lower the energy consumption and with modern technology considerable energy savings have been realized. Advanced control strategies and optimized building control systems are ways to potentially further reduce the energy demand.

Braun (Braun 2003) and others refer to significant savings potential when
the building's thermal mass characteristics are included for the control optimization.

Potential savings are sensitive to many factors, including utility rates, type of equipment, occupancy schedule, building construction, climate conditions, and control strategy. The analysis of theoretical energy savings showed that the largest potentials are for building zones connected with large energy fluxes as solar gains or internal gains (Gyalistras and

Gwerder 2010). However, these factors, relate to environmental or occupancy impact and thus are uncontrollable disturbance variables to the building system.

To get to these potential energy savings – using the buildings thermal mass and providing for the environmental and occupancy impacts – advanced control strategies have been developed. They go from the classical 'reactive' control methods and move to 'proactive' algorithms. Furthermore, they allow to refine the optimization by trying to find optima, best satisfying multiple objectives.

Model based control – Model predictive control

Model-based control is a control strategy based on testing a set of potential control actions (controller output variable, manipulated variable) on a mathematical model which is a representation of the actual controlled system. Model predictive control (MPC) is a model-based control strategy, widely used in industrial control. The simulated future system states of various input sequences are compared within a defined time horizon, and the sequence minimizing a cost function is adopted as the control action for the next time step. After that time step has elapsed, the simulation/optimization procedure is repeated.

The model needs to have an adequate structure, parametrized to approximate the dynamic characteristics of the actual system with adequate accuracy. The simulation not only is based on current system states but allows to include estimates and forecasts of disturbance variables (e.g. external climatic conditions, occupancy effects).

The selection of a control action, based on simulated future response under future/forecast impacts ranks this control strategy to be a 'proactive' control approach.

Advantages of the model predictive control strategy are:

- with the dynamic behavior encapsulated in the model, the MPC has the potential to exploit the building's thermal storage capacity (Gyalistras and Gwerder 2010).
- MPC can include forecasts for external impacts or boundary conditions in the simulation process
- model based control also work well in context with the control of multiple-input/multiple-output systems (MIMO). The model represents the dynamic interrelations between the input and output states. The simulated results are measured and ranked against the criteria of the objective function. Depending on the structure and parameters of the objective function, unwanted dynamic cross

effects can be minimized. The model-based control thus inherently represents a multi-parameter controller.

- MPC can take actuator limitations into account (actuator range, energy supply)
- with the flexible definition of a cost-/objective function it can be easily adapted to different tasks and optimization criteria (e.g. economic model predictive control EMPC, where economical parameters and terms (cost, energy cost) are included in the cost function for optimization.
- apart from the applied underlying dynamic model, MPC can be seen as modular control function block.

Model predictive control with adaptive models

The dynamic building system can significantly change during the utilization phase. From changes in the room layout and utilization category to refitting projects. All these changes need to be mapped to the building model for the model-based control.

Adaptive algorithms are designed to 'adapt' the model based on the measured inputs and outputs of the dynamic system and change its structure and/or parameters. The model predictive control thus can be made very flexible or robust against structural building changes.

Distributed model predictive control

Distributed MPC has been developed for large systems where a central MPC was not feasible. Interdependent subsystems are controlled by their own MPC, which are communicating among each other. Depending on the overhead communication, the local MPC's are optimizing their control actions for the respective subsystem only; or perform a coordination function for the impacts between the distributed subsystems.

Artificial intelligence approaches

Control techniques based on the AI approach have entered several engineering applications. The methods include e.g. neural networks, fuzzy logic techniques, and genetic algorithms.

AI based methods do not require specific models of the dynamic system, but they do require a lot of measured data for the learning process. If enough data is available, the learning AI approach facilitates the implementation. However, it is hard to put the learned/derived model in relation to the physical system. It is not suitable for optimization

processes and the learning process does not work well with changes in the system (e.g. physical changes in the building, occupancy behavior).
AI techniques have been proposed in the field of forecasting. They are used for forecasting short- and long-term climatic impact variables (weather, irradiation, etc.) and building energy use. These forecasts can be used for the model predictive control to calculate the trajectories of system output states for a set of potential control values.

2.3.7 Automation- vs. control hierarchy

In the technical domain of automation – with classical closed loop control as one of its subsections – the tasks are also centered around a technical process. With actuators/devices to influence, and sensors to measure the process parameters, the automation system covers information acquisition and -processing. Internal communication systems (networks) provide for data exchange and external interfaces.

Industrial and building automation covers a wider range of approaches of automation process compared to classical closed loop control theory. Nevertheless, it is worth comparing the established hierarchical automation structure to the proposed hierarchical control structure.
Furthermore, setting a hierarchical control concept in relation to the well-known 'automation pyramid' supports the goal of an intensified inter-domain communication and better understanding and acceptance in the automation and IT domain.

Industrial automation of complex processes also requires the decomposition of the total system to more tangible subsystems. As the previously discussed multi-level hierarchical control for complex system control, automation industry also applies to distributed control systems with process coordination assigned to a hierarchical controller structure. The multiple hierarchy levels are described in the 'automation pyramid'. Figure 2.40 compares the levels of automation (left) to those of the hierarchical control approach of the thesis (right).

The automation pyramid was developed for the classification of control technology systems. Each hierarchical layer represents differing functional requirements, specific tasks and roles within the overall system. The higher up the level, the more the information on the system gets aggregated, and the further down the more detailed and field-relevant information about the process is available.

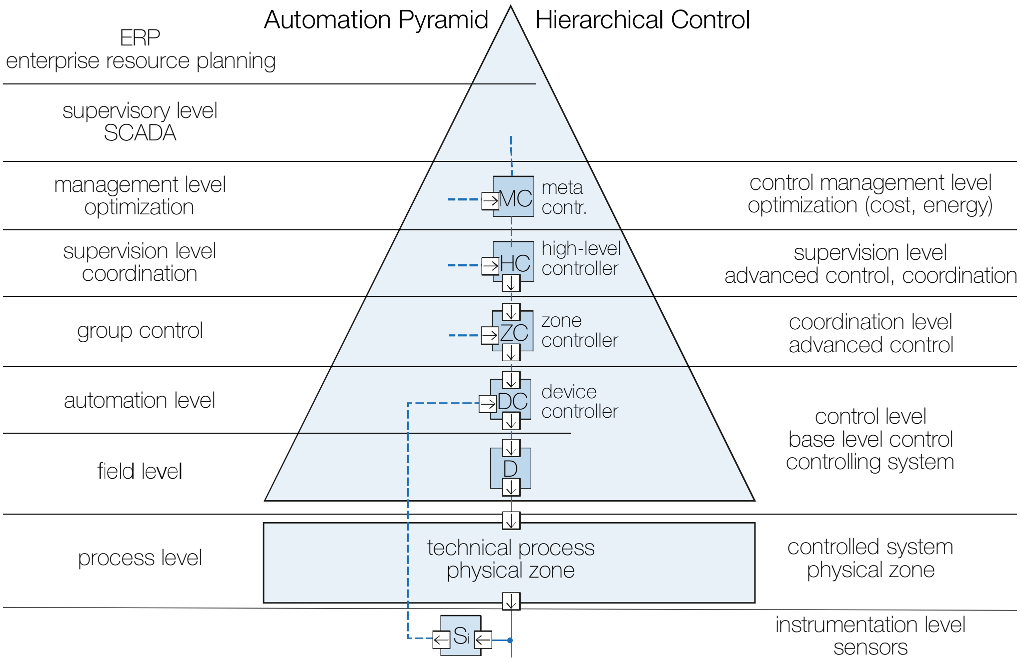


Figure 2.40 – automation pyramid

The structure and principle task assignment of the previously derived multi-level hierarchical control is directly comparable to the hierarchy concept in automation engineering. An overview comparison of these two related hierarchical system concepts is shown in figure 2.40 shows a comparison.

Automation/hierarchical control hierarchy levels:

- Field level – controlling system/elements

  The field level is the lowest level of the automation hierarchy, controls the technical process and includes field devices like sensors and actuators/devices. The actuators/devices manipulate the technical process and sensors convert real time process parameters and provide data for the automation system network.

- Automation level – control level

  The control level contains the base controller structure. The controller drives the actuator/device based on control deviation and sensor signals. In industrial automation Programmable Logic Controllers (PLCs) are widely used as controllers, programmed to execute automatic operations sequences.

- Group control – coordination level

  The first coordination level aligns the MIMO system, aggregated from several SIMO control circuits. In automation the group level also aggregates systems of the automation level.

- Supervising control level – advanced control and coordination
  This layer provides coordination functionality, setting overall system targets, breaking them down to subsystem targets. The Supervisory Control and Data Acquisition (SCADA) functionality is also located on this level.
- Management level – control management level
  In this top level of the industrial automation pyramid, the entire automation system is managed. The tasks of this level include more commercial and logistics aspects of the automation system and the automated process.

2.4 Summary – zone- and control concepts

This chapter developed the necessary base elements towards a scalable and automatable process for the generation of a hierarchical control scheme for complex building control systems (see chapter 3).

A modular zone concept based on physical effects initiated by controlling devices was developed. From a simplified system approach, the involved elements were adapted to a more versatile and flexible system type approach. The physical zone as base module was introduced. Preassigned system description elements (ports, terminals, relation paths) facilitate a simple way and a scalable approach to complex building system configurations. The approach to system mapping with modular elements underlines the comprehensible concept. The modules also provide domain-specific system views (building physics, control engineering, IT, etc.).

A spatial decomposition of a building structure was discussed in order to reduce system complexity into more manageable and smaller subsystems.
To align the effect-based modules with a spatial building decomposition, the effect-based zone concept and boundaries have been set in relation to geometric type boundaries.

To embed the structure and process into an existing data standard, the decomposition accesses the IFC spatial data structure (also in line with the spatial structure as per VDI 3813) and breaks the building system down to a space or subspace level (physical zone).

On the other hand, the zone concept serves as basis to develop complex control circuits in a modular way. From simple SISO to MIMO systems, and from single parameter control to multi-parameter control.

To manage the MIMO control a hierarchical control approach was presented. Finally, the hierarchical control approach was put in relation to the hierarchical structure in the automation industry, referred to as the 'automation pyramid'.

The strictly modular approach provides a simple but effective way to work with the zones and map control related elements. A hierarchical control structure lays the base towards a scalable control structure. Figure 2.41 presents the derived relation of the spatial decomposition, the mapping elements and the hierarchical control concept.

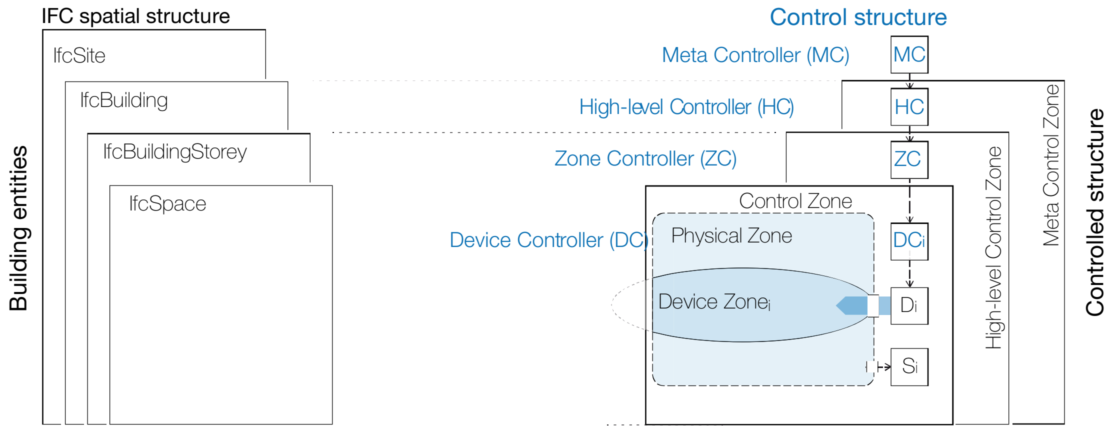


Figure 2.41 – from spatial structure to control structure

The zone structure provides the basic elements for the mapping of physical systems contained within an architectural building structure. The zone concept allows a systematic compartmentalization and structural modelling of a building and its control system into flexible sub-entities.

3 Control Structure Generation Process

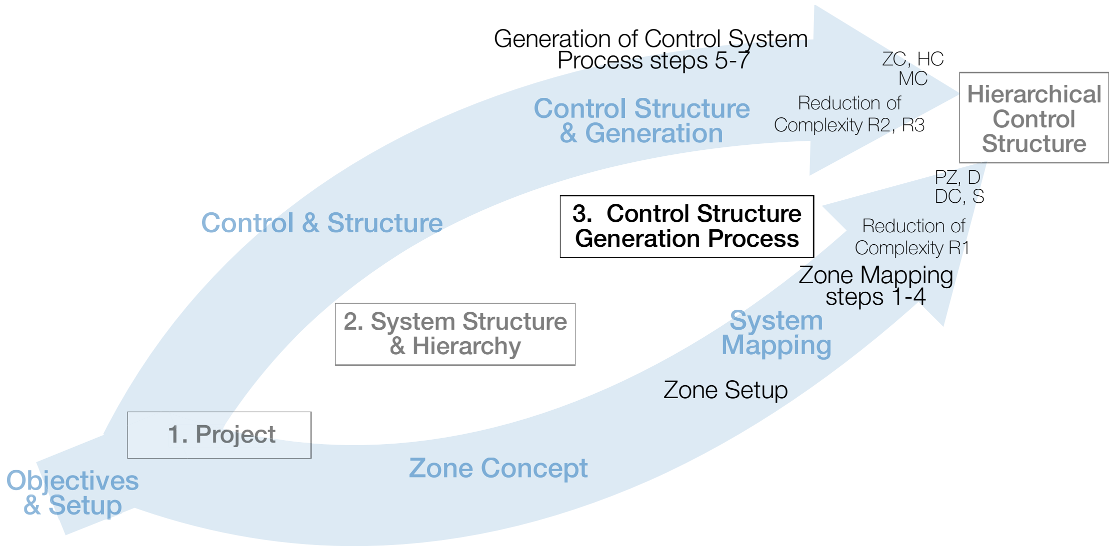


Figure 3.1 – structure chapter 3

This chapter leads through the process steps of the automated generation of a hierarchical control structure as basis for control related views and inter-domain process management.

The three-stage process – setup, mapping and control structure - takes from data from a building data model to a control structure proposal (see figure 3.2).

Throughout the process, the focus remains on a systematic and straightforward approach, which is easy to understand, readily applicable and easily implemented. This work also addresses additional ways to provide the results in domain specific views in order to facilitate the inter-domain project coordination.

The developed method focuses on the scalability of the underlying structure, as e.g. for large and complex buildings, and the integration into automated processes.

3.1 Process from IFC data model to control structure

The principle process steps from the IFC data to a hierarchical control structure are shown in figure 3.2:

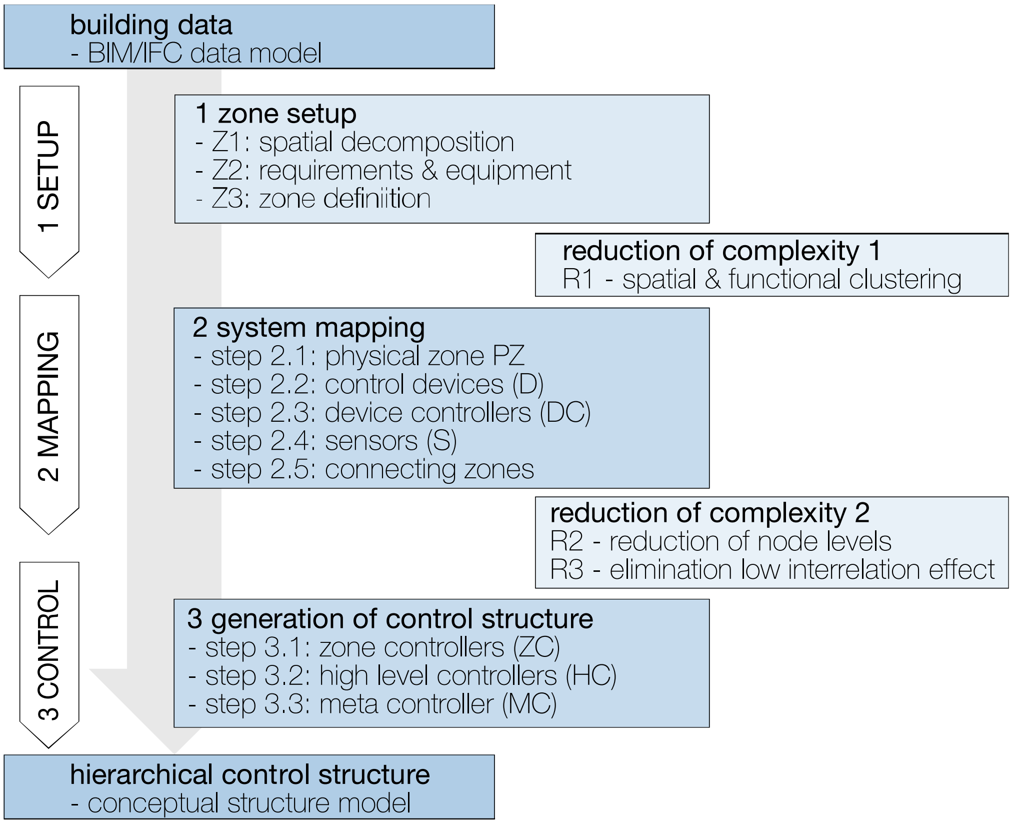


Figure 3.2 – process from IFC to control structure

The principle process steps are:

- **Zone setup**

  The zone setup process accesses the building data from the IFC data structure of a BIM model and prepares a spatially decomposed building structure for the zone mapping. This includes the definition of zones (at space-, sub-space- or aggregated space level) and the completion of equipment profiles (devices and sensors).

- **System mapping**

  The physical system and the building equipment are mapped to zones (device- and physical zones) within spatial entities.

  The physical zone as controlled system and the controlling system with modular control elements, as controllers, devices and sensors, are the base for classical closed-loop control systems. This mapping establishes the effect relations of control actions, including primary- and secondary effects as well as cross effects between zones.

  A modular approach and a construction kit like process facilitates this mapping.

- **Generation of hierarchical control structure**

  The third process stage describes the generation of a control and coordination structure. This work proposes a new, scalable and converging method and set of generative rules towards the structural configuration of a multi-level control logic.

  The rule-based procedure for the definition of the higher hierarchical levels of a multi-level control logic scheme and the assignment of the coordination tasks takes a different approach than proposed in previous publications (Rader and Mahdavi 2015, Mertz and Mahdavi 2003).

  Special focus is on the scalability of the underlying structure, as e.g. for large and complex buildings. The proposed steps and rules for a control scheme generation can be processed in an automated process.

  This chapter continues in the sense of the structural approach and adds a hierarchical system aspect for the generation of the control scheme.

  For the first coordination control level (zone controller, ZC), the controlled system consists of the above described aggregation of SIMO systems (several device controllers and the affected physical zone). Controller at this level influence multiple lower-level controllers. Their controlled system has multiple inputs (one for the target value for every device controller) and multiple outputs and thus forms a typical MIMO system.

  The multi-level control hierarchy assigns specific coordination and optimization tasks in each of the levels created.

  - The first hierarchical controller level – zone controller, ZC – coordinates in case of more than one device impact on a single system output or state.
  - The second level – the high-level controller, HC – coordinates for more than one zone controller acting on one device controller.
  - The last level the meta controller, MC – coordinates the targets for the respective highest-level controllers in the line of control command.

- **Reduction of system complexity**

  Looking at entire buildings and their large number of spaces and zones, each containing numerous interrelated effects, the mapping process leads to a highly complex model. This subsequently translates to involved computational effort and high number and complexity of higher-level controllers (ZC, HC). Hence additional process steps towards a reduction of complexity are applied:

- Before running the generative algorithm, zones and/or spaces are tested for potential clustering. The control scheme is then generated with one representative elements of each cluster.
- Reduction of graph nodes within the control zones: an extensive number of nodes and edges are initially provided with the physical zone modular base element for the modular pick & place functionality. In this step, unused nodes and edges are eliminated.
- Applying a minimum threshold for the induced primary and secondary effects and cross effects. When passing an effect through more than one physical zone or propagation type, their impact magnitude weakens. In case attenuation factors (edge weights) were assigned, some aggregated cross effects will show a relatively low estimated level of impact. If below the threshold, these impacts can be disregarded for the overall structure. For the control, these residual cross effects will then be treated as a disturbance variable.

Sample setup

Throughout the explanation of the process – system mapping and generation of the control structure – a simple sample/setup serves as an example.
A single room is affected by control actions from four devices - external shades, window, radiator, and a lighting equipment. The controlled variables are air temperature, relative humidity and CO_2 content as well as the illuminance.

Figures 3.3 and 3.4 show the sample setup's floorplan and initial system graph.

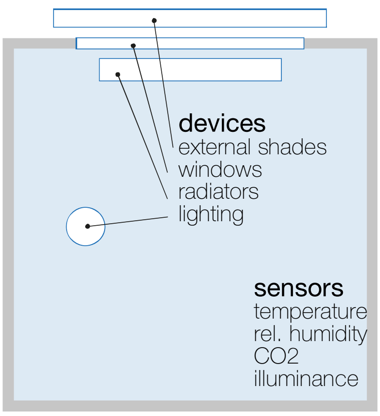


Figure 3.3 – sample setup, floorplan

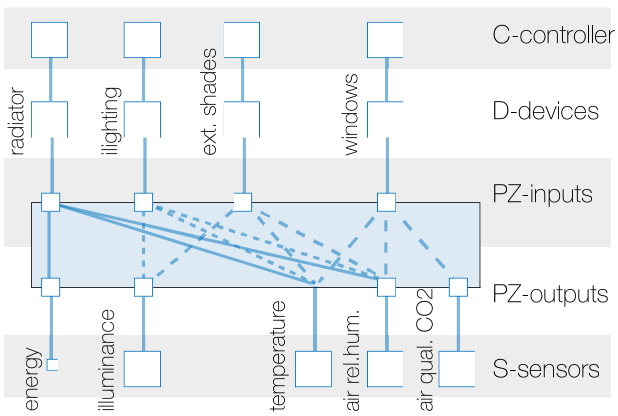


Figure 3.4 – sample setup, initial system graph

3.2 Zone setup

3.2.1 Step Z1 - Spatial decomposition

To reduce the system complexity the building model is spatially decomposed into smaller units, all the way down to the physical zone and 'control zone' level.
Based on the BIM framework, the data objects, attributes and relations for the spatial decomposition can be extracted from the IFC data model. The hierarchical spatial structure of the IFC data allows to computationally break the building down into storeys and spaces. The IFC data model also holds data on assigned technical equipment with its relations into spaces.

3.2.2 Step Z2 - Requirements & equipment

All relevant requirements for the BACS are collected, either from the IFC attributes, deducted from utilization types (VDI3813-1, room utilization types, occupancy planning and room types) or inquired from other sources as planners or owners. Requirement profiles reflect all stipulations as to the quality of the working or living environment, especially the aspects of thermal and visual comfort and air quality demands. These requirements translate into the choice of equipment to be employed.

The equipment data is either available within the IFC data model or needs to be completed manually.

The selected devices have to sufficiently influence the targeted set of system output states (manipulated variables with boundary conditions). The configuration needs to be altered in case the device does not affect the controlled variable (non-controllable variable) or the sensor is not within the respective device zone.
The selected controllers, devices and sensors are integrated as modular system elements in a 'pick and place' like manner. The respective data can also be managed via templates, similar to templates of other software tools working with BIM/IFC (Kabitzsch 2018, Dibowski et al. 2006). These templates also allow to edit the equipment, change their impact weighing and to overrule any predefined settings of the physical zone module.

3.2.3 Step Z3 - Zone definition

In the case of a one-to-one relation between a geometrical space and a physical zone the data can be directly accessed from the building model. For complex or large space

geometries and areas showing differing internal characteristics, conditions or constraints, several physical zones within one architectural space can be specified and be put in relation with each other (Wong and Mahdavi 2000).
In case of a 1:n relation of a space to its zones the control elements & devices have to be assigned to the respective zones (subspaces, PZ's).

3.3 Reduction of complexity R1

3.3.1 Step R1 – Space/Zone clustering

Before running the mapping and the generative process, the system structure can be tested for potential clustering, to reduce the large number of entire building's spaces and zones.

Space characteristics

Spaces/zones are assessed for sharing similar characteristics such as

- common control related equipment
- interactions between control actions,
- relations to external conditions (external/internal walls, orientation, windows, etc.),
- thermal requirements
- utilization, function purpose
- occupancy impacts, behavior and schedules, number of individuals
- similar areas or volumes
- geometric adjacency relations (strict adjacencies), functional adjacencies, distance relations (Mahdavi et al. 1998)

3.4 Zone mapping – Steps 1-5

The first process steps guide through the modelling of the principal control relevant elements and their relations within a control zone as well as the interrelations between such zones.
In a modular process, devices, controllers and sensors are mapped to the physical zone by selecting the respective ports/terminals from the predefined PZ module. For the primary effects, this results in a set of basic control circuits (SIMO) within the physical zone related to a building space or -subspace.
The mapping yields a structural system view on physical effects of control actions within and across physical zones.

All described steps are performed within the adjacency matrix representation.

3.4.1 Step1 - Physical zone (PZ)

The physical zone element is the base element of the modular zone construction kit.
For the zone concept, the PZ is the pivoting element for actions induced by the respective controlling elements. The physical zone maps the primary and secondary effect relations of a specific input parameter to the PZ's output state space.
The predefined PZ block has ports for linking device modules and terminals for the sensors. The PZ module provides an initial set of predetermined primary and secondary effect relations between device actions (system inputs) and their resulting system states (system outputs).

3.4.2 Step2 - Controlling devices (D)

To satisfy a specific given comfort requirement (e.g. room temperature for thermal comfort) selected devices are connected to the respective ports of the physical zones.
In the modular kit concept, this can be depicted as a set of devices being plugged onto the respective input ports of the physical zone module, as shown in figure 3.5.

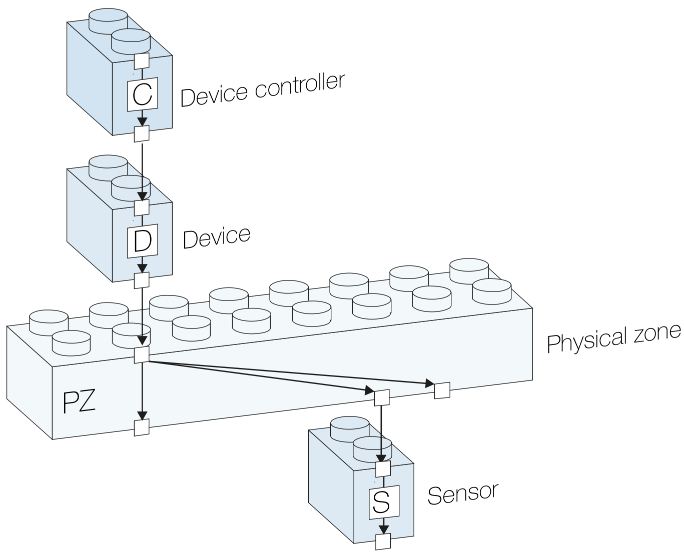


Figure 3.5 – modular kit concept 1

3.4.3 Step3 - Device controllers (DC)

In the course of this thesis, it is assumed that all controlling devices are operated by device controllers (DC). These DC modules are linked to their respective devices.

3.4.4 Step4 - Sensors (S)

In this process step, appropriate sensors for the type of controlled variable, are linked to the physical zone. They provide PZ's output state measurements to the control system. The feedback connection is considered to work via a network, thus its graph representation is omitted.

Sensor elements can represent physical sensor modules or virtual sensors. Virtual sensors use available measurements and other process parameters and calculate/estimate other states or process parameters of interest by using mathematical models (e.g. comfort by PMV value). These can be necessary in cases where the sought state cannot be measured by a physical device, an installation is not possible or economically not feasible.

3.4.5 Control zone – system & control circuit

The set of base elements as controller, controlling elements (actuator/device), controlled system (physical zone) and sensor corresponds to a discrete single-input/single-output (SISO) closed-loop control circuit, with the primary effect output as controlled variable. Taking the secondary- and cross effects into consideration, the SISO systems become single-input/multiple-output (SIMO) systems.

Figure 3.6 shows a basic control circuit, the feedback connection is considered to work via a network, thus it is omitted.

This mapping reflects the effect paths of induced control actions, from controller via device to physical zone and sensors; including primary-, secondary- and cross effects.

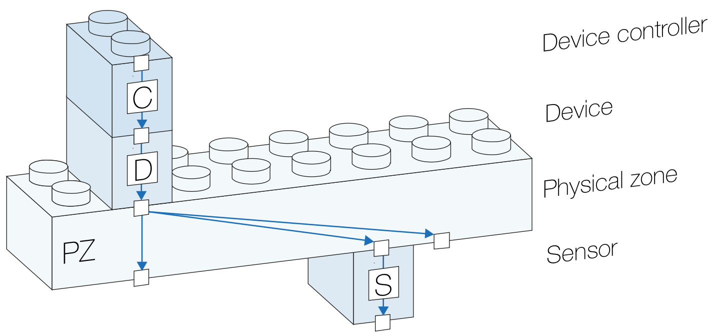


Figure 3.6 – modular system mapping 2

From SISO to MIMO systems

Aggregating several devices acting on device zones onto one PZ will thus superpose each of the typically single-input/multiple-output systems (SIMO; one action, primary- and secondary effects). The physical zone as controlled system is then a multiple-input/multiple-output (MIMO) system (see figure 3.7).

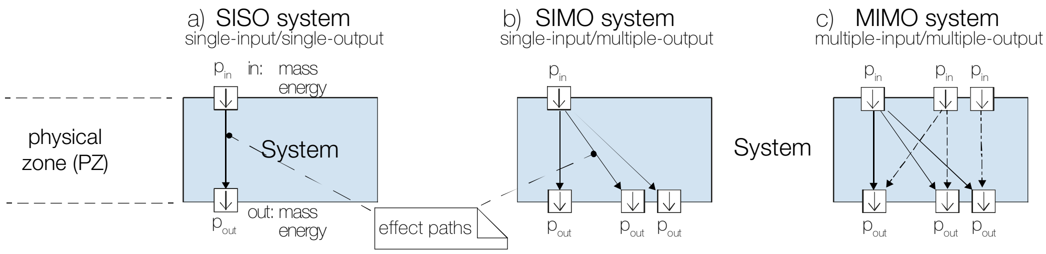


Figure 3.7 – SISO, SIMO and MIMO systems

The complete setup of a control zone in 'LEGO-terms' results in a system description as shown in figure 3.8.

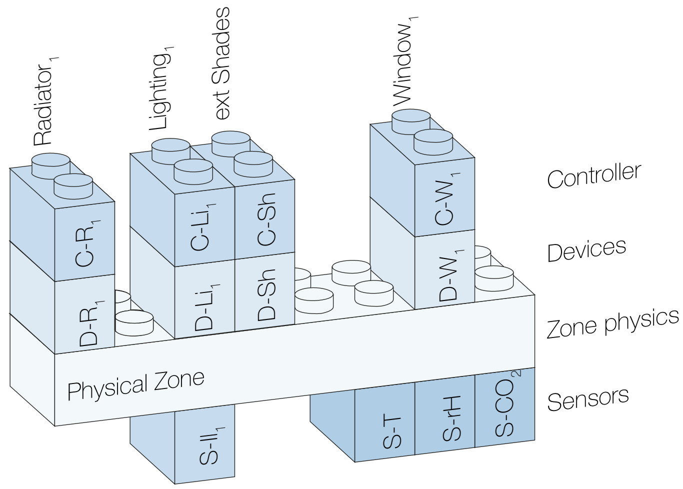


Figure 3.8 – modular system mapping result

Zone description methods

The simple representation of a modular zone system mapping in form of a LEGO-set only was selected to illustrate the mapping process using pre-defined modules docked to a physical zone. This depicted LEGO composition is helpful to visualize the modular setup, but of course is not an engineering type approach. It cannot translate to an automated process, nor does it satisfy system specification needs of the involved engineering domains. Of course, the zone mapping and the underlying subsystems with modular system elements can be presented in various, more technical views, as control view, SysML views, graph view and matrix view.

Control view

Control views are usually shown in form of block diagrams. Figure 3.9 shows the sample setup in such a block structure; a simple SISO control circuit on the left. However, for more complex structures and/or with systems incorporating several physical zones, such graphs are quickly getting visually cluttered.

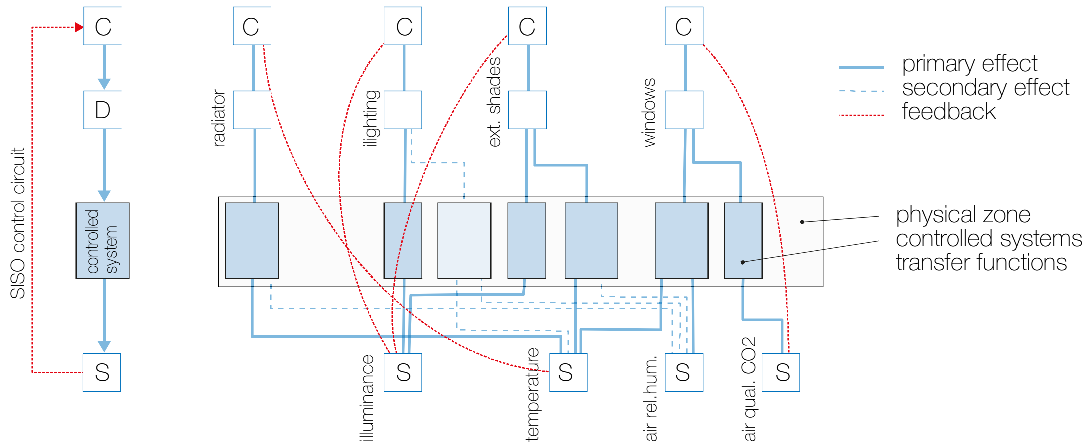


Figure 3.9 – system mapping – control view

SysML-type view – internal block diagram

SysML is a general-purpose graphical modelling language and supports the specification, analysis, design and verification of complex systems. With its graphical representations it is capable to represent the main aspects in a flexible way and to cover different domain-specific modelling techniques.

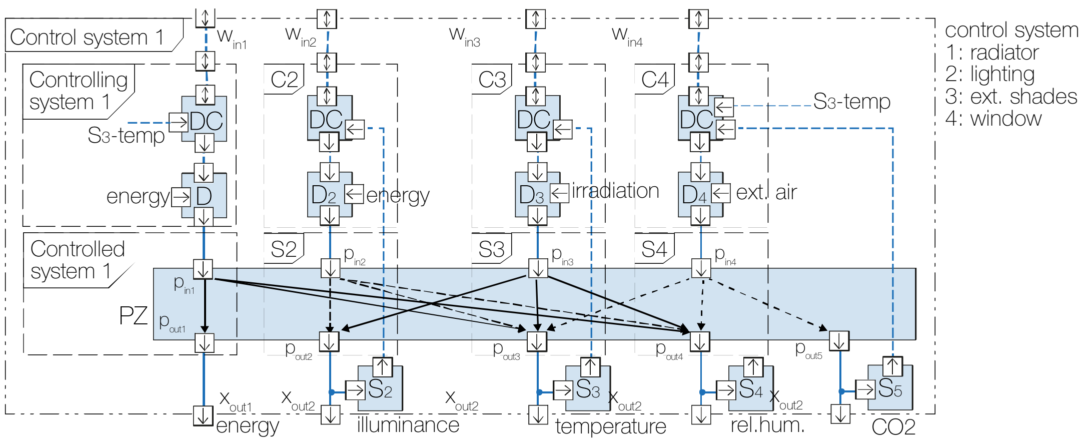


Figure 3.10 – system mapping – SysML ibd view

An internal block diagram (ibd) provides the internal view (white-box view) of a system block. The ibd-graph shows internal parts, flows and interaction points (ports and terminals) with other elements of the system (SysML 2018). Figure 3.10 shows a SysML-style internal block diagram of the sample control zone.

Graph view

Graphs are visualizing structural relations and provide a way to present the modeling of relations between discrete entities and dependencies within systems. Graphs consist of nodes (representing controllers, devices, sensors and the physical zone's ports/terminals) and edges, representing the effect- or flow path (energy, mass flow or information).

Figure 3.11 shows the sample setup in form of a graph. The causality relation within the control circuits are represented by directed graphs, with a defined direction for the vectors/edges.

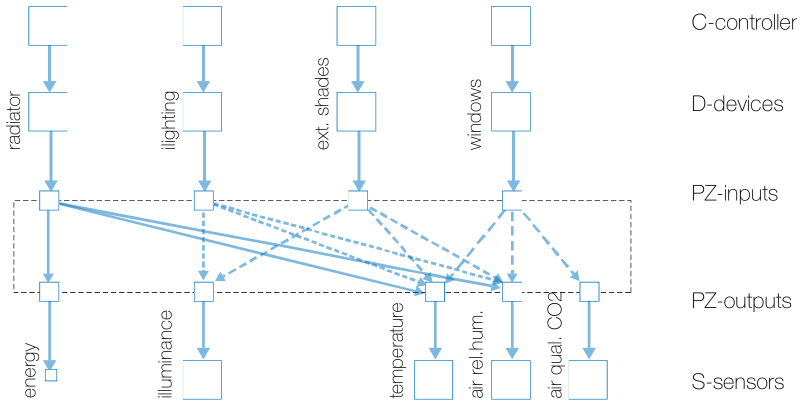


Figure 3.11 – system mapping graph view

For more complex systems and aggregation of subsystems, the graphs quickly become very dense and confusing. Therefore, node-edge diagrams are not a good choice for displaying complex systems with many nodes and edges.

Matrix view

The graph data specifying the node relationship can also be described mathematically in the form of a matrix, referred to as adjacency matrix. Adjacency matrices offer a compact representation of graphs (Shen and Ma 2007) and thus a more suitable representation of complex systems or dense graphs. In an adjacency matrix, the nodes are assigned to the rows and columns; non-zero matrix elements indicate a presence of a connection.
The elements can also store a weight, in the case of the physical zone the values of the non-zero elements represent the effect attenuation estimates between two nodes. Edges defining an information transfer do not have an attenuation, their edge weight equals 1.

For the physical zone the causality relation of input and output states are represented by directed graphs; such graphs translate into a non-symmetric adjacency matrix.

As the modular block scheme of the structure itself, the hierarchy representation within an adjacency matrix can be built in a modular manner. Figure 3.12 shows the internal structure of the adjacency matrix with the zone sets on the diagonal. Connections within zones are represented by submatrices within the adjacency matrix. Physical zones are a further subset to these block matrices.
The links between modules are represented in the off-diagonal elements above or below the submatrices.

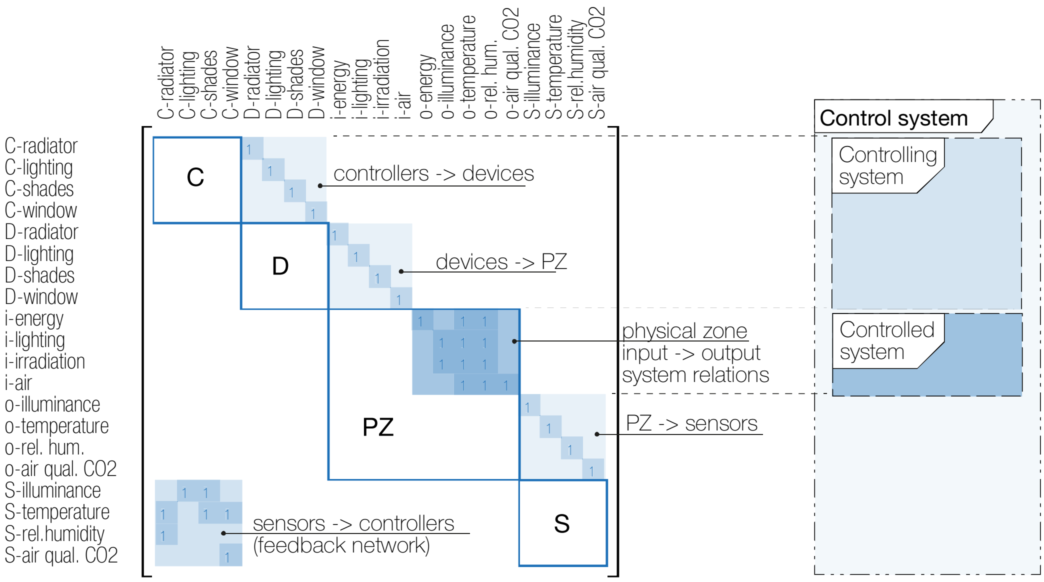


Figure 3.12 – system mapping - matrix view

The matrix representation is very useful as it links graph theory and matrix algebra. A description using adjacency matrices allows graph manipulations by operating within the algebraic space of matrices. Matrices facilitate computation operations and aggregations of complex underlying systems and thus enables a scalable system approach.

3.4.6 Step5 – Interconnecting zones

In steps 1-4 the building system is mapped onto the control zone level. In most cases the control zone level will be equivalent to the building's space or subspace level.
For the system aggregation from zone level to combined structures, the interrelations between physical zones have to be put in a structural context.
To account for cross effects between zones (e.g. heat transfer through walls, cross ventilation through doors, etc.), the respective zones need to be linked. This is done by

connecting the output ports of one physical zone with the respective input ports of the affected zone.

Geometric relations

Adjacency relations are examined for further reductions:

Simplified sample simulations have shown big thermal time constants and a high attenuation for effect transmissions across walls. When excited with sinusoidal input signals (e.g. air temperature changes in one space) the transmitted effect magnitude is reduced even further to a very low level.

Insignificant effect propagation is also expected in case of a small overlapping wall area or for adjacencies across the edges of spaces (e.g. across connecting corners).

An equal connection process is necessary for linking special constructs as units (U) or elements (E). These can affect several zones (e.g. exterior shades across multiple rooms) or control units with their own control system (e.g. HVAC systems, mechanical ventilation, etc.).

Figure 3.13 shows a sample of zone interaction modes. The control unit's (U) physical zone of subsystem 3 impact two other zones (zones 2 and 4). On the other hand, the zones 4 and 5 show a cross-relation and affect each other.

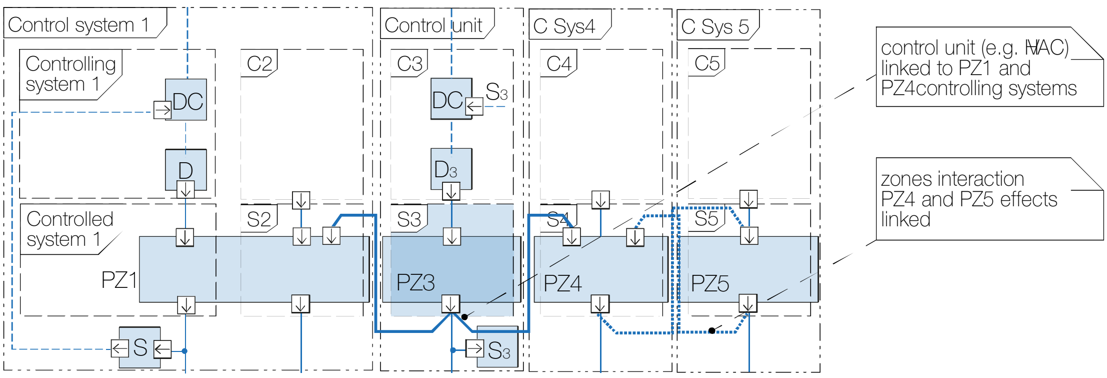


Figure 3.13 – system mapping – zone interrelations

3.5 Reduction of complexity – R2 & R3

3.5.1 Step R2 – Reduction of nodes

This process step involves a reduction of graph nodes. The physical zone module is preset with an extensive set of potential internal primary- and secondary effect paths for a variety of device types. Thus, an extensive number of nodes and edges are initially provided with the physical zone base element, but not all of them are used for the mapping of a building zone.

Reduction process:

- unconnected PZ nodes/edges

  In this step, nodes and edges of the physical zone which are not connected to any device, sensor or port of an adjacent physical zone are eliminated.
- level of devices

  Under the assumption that devices always have a device controller the displayed level of devices, used for system deduction reasons, can be discarded. The device is represented within the device controller level (controlling elements)
- PZ's ports and terminals

  To simplify the graphical representation also the physical zone's ports and terminals are eliminated.

As a result of this reduction process, the device controllers and their impacted effects captured by sensors show as directly linked.

This presentation corresponds to the pursued simple action-response graph concept as shown in figure 2.3).

This reduction process does not have any limiting effect on the mapping of physical impacts nor an implication on the overall control structure.

Figure 3.14 shows the sample room's initial system graph (left) and the status after step R2 (right).

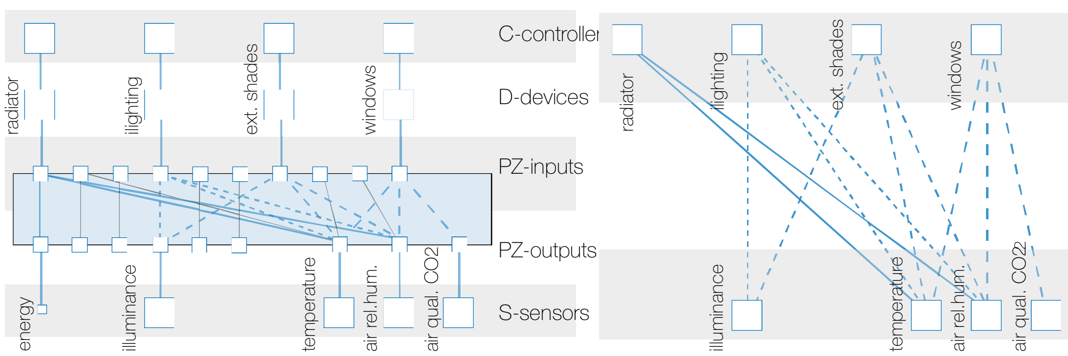


Figure 3.14 – reduction of complexity R1

3.5.2 Step R3 - Elimination of low-level effect paths

In case the optional edge weights have been assigned in the graph/adjacency matrix, this process step reduces the number of low effect cross relations in and between physical zones as well as other type zones (units and elements).

As mentioned before, the edge weights of the effect relationships (graph representation) relate to the adjacency matrix elements Aij ($0 \leq Aij \leq 1$); they represent an estimated relative magnitude of the induced primary and secondary effects. When propagating an effect with an attenuation $Aij < 1$ through more than one physical zone, its impact magnitude weakens (combined effect = product of edge weights on the path). Consequently, some of the secondary effects can show a relatively low estimated level of impact. In such cases, the respective impact can be disregarded for the control structure (connections with Ai ≤ residual limit). In control theory terms, these residual cross effects will then be treated as a disturbance variable.

3.6 Generation of the control structure

In the first part the building structure has been spatially decomposed, and control relevant elements have been mapped to control zones to a building's space or subspace level. When aggregating the SISO and SIMO structures of several device zones, the physical zone as controlled system becomes a real multiple-input/multiple-output (MIMO) system. This MIMO system is controlled by a set of controllers and their respective devices. Each of these controllers act on a controlled SIMO system with the primary effect parameter as its controlled variable. Disturbance effects from other control circuits also affect the physical zone.

These described control elements – device controller and devices as controlling elements, and the physical zone/device zones as controlled elements – are combined into a control zone. For a next hierarchical control level these control zones represent the controlled system and exhibit multiple-input/multiple-output (MIMO) system characteristics.

As described in chapter 2.3.3, the control of MIMO systems is more complex than controlling SISO systems. Multi-parameter control systems are systems where multiple control parameters of a MIMO system are controlled simultaneously and where the manipulated-/control- parameters are strongly coupled.

The controlled system, with its numerous physical zones and cross-relations, is highly complex. For the building structure it is not practical to create a global building control in a form of a single monolithic control system. Apart from the involved system complexity and scalability issues, this is not suitable for integration of additional BACS tasks. Such tasks not only involve control tasks but also control optimization processes with different target settings as to achieve optimal comfort criteria, energy savings, and optimization of other economical parameters.

Hierarchical control structure

Different approaches to MIMO control have been presented in chapter 2.3.3.
Integrating control coordination levels and generating a hierarchically organized control structure is a scalable approach to MIMO control.
The hierarchical control approach has been selected based on the advantages as being:

- capable of coordination tasks for MIMO systems
- suitable for an automatable generation process
- flexible with respect to changes of the building spatial setup
- adaptable to optimization processes with differing objectives
- provides scalability of the overall control structure
- relatively robust against failure on lower controller levels,

This makes it a highly promising approach and thus was the selected control form for this control structure generation process.

A multi-layer hierarchical control, with more than one coordination layers allows to integrate the interrelations between and within the subsystems. The coordination strategies, and the subsystems hierarchical target values can be coordinated in view of a more holistic optimization process. Conflicts of objectives can be addressed in the coordination layers of the hierarchical control structure by different strategies, e.g. rule-based, by more involved multi-parameter optimization and/or model-based control algorithms.

Coordination function

For setup and parametrization of controllers it can be problematic to govern very different dynamics in terms of controlled system's time constant within one single controller. Especially for optimization processes such multi-time-scale dynamics are difficult, a situation that can be handled through a temporal decomposition of the control system.
Different strategies tend to partition the control as e.g. in form of cascaded control (see chapter 2.3.4) where the different ranges of system time constants are dealt with different

cascaded controller levels. The fast dynamics are controlled by the inner control circuits, the slower systems/parameters by the outer control circuit.

In the case of building control, the controlled systems exhibit very different dynamic response and a wide range of time constants. From time constants of basically zero as in the case of light to rather slow systems as floor heating in terms of air temperature as the controlled variable.

The first control elements/circuits acting within the control zones – device controller, device, physical zone, sensor – can be easily parametrized to the respective device controller and SIMO subsystem (primary effect loop). The control zone itself, as aggregated controlled system represents a MIMO system. The next control level includes a coordination function to govern the control circuits within that MIMO system.

In terms of classical control, the first approach would be examining the dynamic characteristics/response of the controlled variables, respectively their time constants, to assign similar dynamic response characteristics to a coordinator. To manage the multi-time-scale characteristics of building systems, the coordination task thus needs to be decomposed into dynamic response categories, from slow to fast (Xu et al. 2015).

For the many different devices and physical characteristics, it is however cumbersome to first establish all time constants (e.g. by simulation) and then rank and cluster the equipment by their time constant.

When looking at the devices and their dynamics from a different angle, there is a correlation between devices/system dynamics and their primarily designed target effect in terms of a specific comfort type (thermal, visual, air quality).
The category of targeted comfort class correlates with a subrange of dynamic response or time constant:

- instantaneous response/time constant basically zero for light and radiation in general. Acoustics effects also would fall in this category.
- medium range of time constant for air quality and mass flow related effect, and
- slow dynamics and big time constants for effects involving considerable thermal mass.

Figure 3.15 shows this relation of system time constants versus their classification/attribution to comfort aspects.

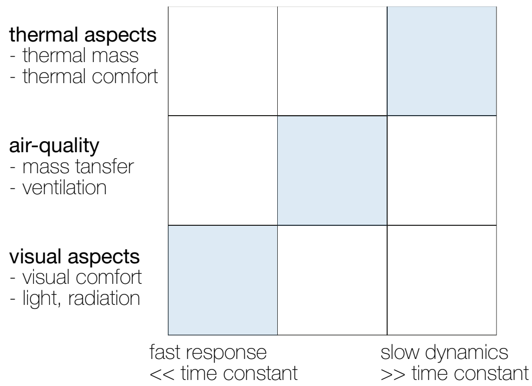


Figure 3.15 – relation system time constants vs. comfort classification

Hence, a reasonable approach for the definition of the coordination is grouping the devices/subsystems according to the targeted comfort type into:

- visual effect coordination – fast dynamics
- air quality effect coordination – medium dynamics
- thermal effect coordination – slow dynamics

3.7 Control level & tasks – steps 6 – 8

Generation Process

The steps towards a hierarchical control structure follow a strictly rule-based process, suitable for automated generation.
Through the stringent definition for the linking rules into zone controllers and high-level controllers, the proposed method is convergent. By the definition of their coordination tasks, the number of zone controllers is limited to 3 per zone (thermal, visual, air quality). The number of high-level controllers is 4 (thermal-visual, thermal-air quality, visual-air quality and thermal-visual-air quality). In most cases they reduce to 2 (thermal-visual and thermal-air quality) with 2 rare control coordination combinations (visual-air quality and thermal-visual-air quality).

The automated generation process is based on the system description in form of a directed graph, respectively by its adjacency matrix. Matrix calculations are suitable for automated processing, and the involved operations can be handled up to considerable matrix dimensions. The process thus remains scalable and can be applied to big size buildings with high complexity of their systems.

In a set of generation rules (steps 6-8) a hierarchical control structure is established to coordinate and manage the control tasks of the previously mapped control zones (steps 1-5).
The generation of the hierarchical control layers relates to additionally available system information as to the categorization of subsystem dynamics of the respective controlled parameter.

The generation rules towards a hierarchical control structure are applied in 3 consecutive steps and result in a 3-level scheme for the building control.

- step 6: **zone controller (ZC)** - coordination of comfort aspects across multiple device controllers (devices) , jointly acting on output states
- step 7: **high-level controller (HC)** - coordination across multiple basic comfort types and their related conflict of objectives (across zone controllers/coordinators resulting from step 6).
- step 8: **meta controller (MC)** - accounting for prioritization tasks among high-level controllers as well as interactions between spaces or storeys.

These steps towards the generation of the hierarchical structure are explained on the previously used sample setup (see chapter 3.1) as shown in figure 3.16.

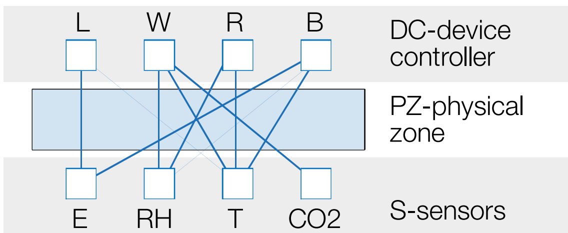


Figure 3.16 – control structure - initial setup

3.7.1 Step6 – Zone controller (ZC)

This layer accounts for the coordination of a comfort aspect across multiple devices and device controllers.

The zone controllers' layer is generated as follows: if more than one device controller DC impacts one measured zone output state (sensor) these respective DC's are linked to one of four zone controllers. The targeted zone controller depends on the dynamics cluster this zones output/sensor signal is attributed to. E.g. a temperature sensor is attributed to thermal effect/comfort, hence the specific device controller is linked to the thermal zone controller). This generation rule is depicted in figure 3.17 and 3.18.

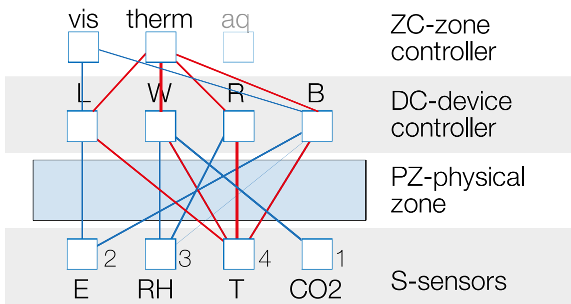


Figure 3.17 – control structure – assignment of zone controllers

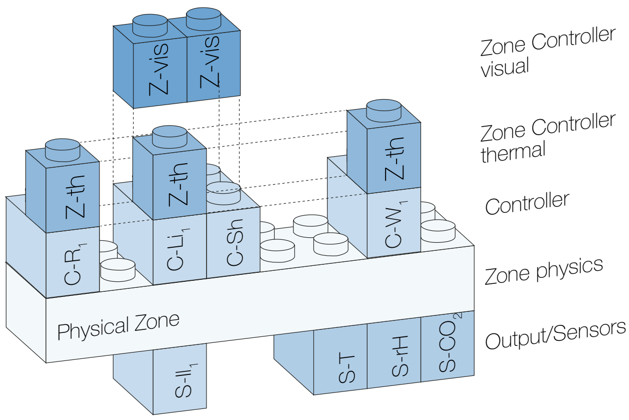


Figure 3.18 – control structure – zone controllers

For the computation process, the system's adjacency matrix is evaluated for the indegree of the sensor nodes (see figure 3.17). Indegree refers to the number of edges pointing to a node in a directed graph. An indegree >1 indicates that the output/sensor node is impacted from more than one device controllers. The device controllers acting via their controlling devices on these PZ input ports are thus jointly impacting the one terminal/output node represented by the sensor node. The concerned device controllers need to be coordinated by a corresponding zone controller. The coordinating zone controllers are assigned based on the (comfort) category the affected output/sensor is attributed to.

For the sample setup the temperature output/sensor has an in-degree of 4 (the output is impacted by 4 different device controllers). The temperature is a parameter adhering to the thermal comfort category, hence the respective 4 device controllers will be coordinated by a zone controller for thermal aspects (ZC_{th}). The relative humidity output sensor node has an in-degree of 3, with 3 device controllers affecting its state. With the relative humidity also pertaining to the thermal comfort category, these three device controllers need to be connected to the thermal zone controller as well, which in this case has already been done through the previous process step for the temperature output. The

Illuminance sensor node has an in-degree of 2, thus the two device controllers affecting this output have to be coordinated in a zone controller for visual aspects (ZC_{vis}). The sensor node for CO_2 level has an in-degree of 1 and does not need any coordination as it is only affected by a single device controller (window).

Previously published methods (Rader and Mahdavi 2015, Merz 2002) also create zone controllers in case more than one impact is affecting a single sensor. However, the created zone controllers do not cluster specific sensor parameter attributes (indirectly relating to the subsystems' time constant). This leads to a higher number of zone controllers which can cause problems with the convergence of the overall control system. That zone controller's assignment results in impact combinations that are not easily related to meaningful building physics topics groups (e.g. comfort groups).

3.7.2 Step7 – High-level controller (HC)

This layer accounts for the coordination across multiple basic comfort types and their related conflict of objectives. This generation rule is depicted in figures 3.19 and 3.20.

In case a device controller (DC) receives control requests from more than one zone controllers, a high-level controller (HC) is assigned to coordinate the actions of these zone controllers. Up to four HC categories are assigned by interdependency types. These categories are referring to the combinations of visual-thermal, visual-air quality, thermal-air quality and visual-thermal-air quality aspects. The common ones involve the thermal-visual and the thermal-air quality relations.

For the matrix operations the indegree of the device controller nodes is evaluated (see figure 3.19).

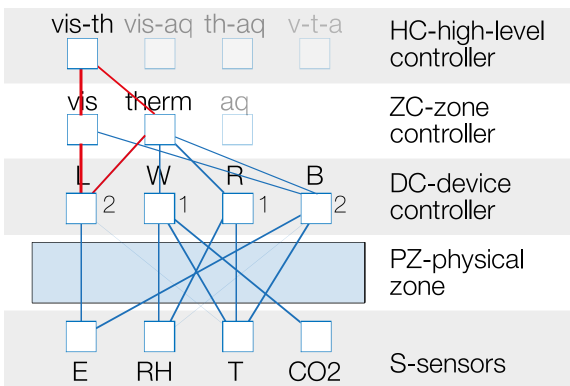


Figure 3.19 – control structure – assigning high-level controllers

The zone controllers acting on these device controllers are coordinated by a corresponding high-level controller (HC). The coordinating high-level controllers are assigned based on the category combination involved zone controllers.

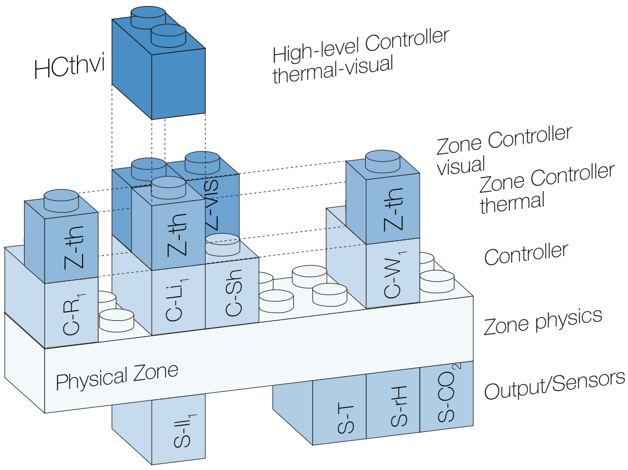


Figure 3.20 – control structure – high-level controllers

Applying this rule to the sample setup, the lighting device controller shows an in-degree of 2, being influenced by two zone controllers (ZC_{vis}, ZC_{th}). To coordinate these two, the thermal- and the visual zone controller, a high-level controller, designated to the visual-thermal conflict is added and linked to the two respective zone controllers. The device controller for the blinds is also affected by two zone controllers. As they are the same as before, no new coordination connection (graph edge) is added. The newly established high-level controller coordinates the visual- and thermal zone controller. It indirectly influences the lighting- and blinds devices via ZC_{vis}, and the devices for lighting, window, radiators and blinds via ZC_{th}.

3.7.3 Step 8 - Meta-controller (MC)

For coordination across spaces and building sections (e.g. storey), all the way to complete buildings, a meta controller is established. The meta controller connects to the spaces' highest controller level. This generation rule is depicted in figures 3.21 and 3.22.

In the case of the sample setup, there is only one high-level controller. This controller is linked to the meta controller. With only one subordinate controller in this case, the meta controller does not act in a coordinating function but provides optimization and setpoint settings for the control hierarchy below.

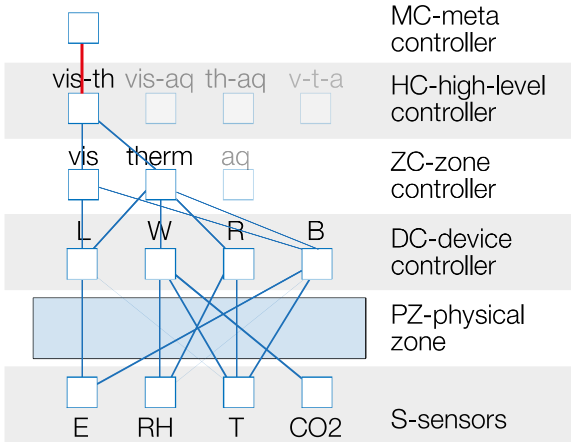


Figure 3.21 - control structure – linking meta controller

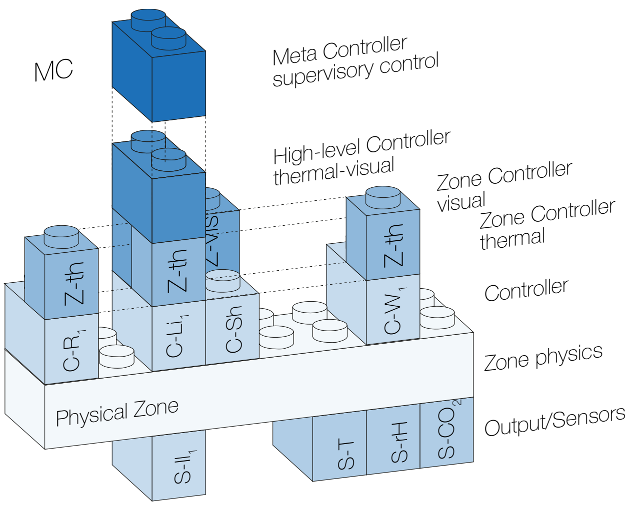


Figure 3.22 – control structure – meta controller

3.8 Example

A floor of an office building serves as an example case. Figure 3.23 shows the floor plan with 18 rooms. 8 offices are oriented towards the north and south respectively, 2 open plan offices extend from the southern to the northern facade. Due to the size and the different external impact the open plan offices are split into two physical zones.

The layout with its setup and employed devices allows a reduction by clustering, leaving 4 room types and 5 zones, the northern and southern offices, the hallway and the open plan office with its two internal zones (see figure 3.24).

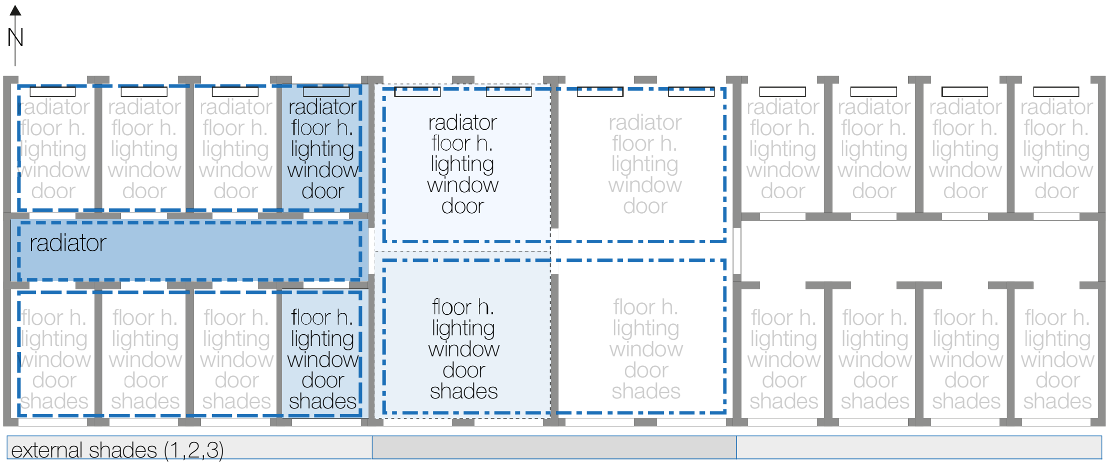


Figure 3.23 – example - floor plan

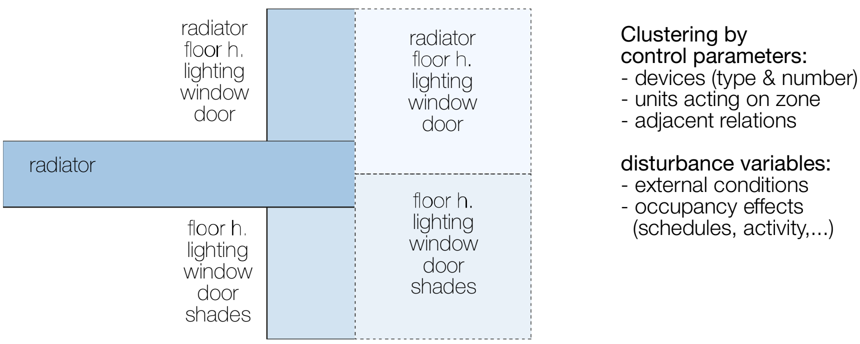


Figure 3.24 – example - reduced floor plan

Figure 3.25 shows the mapping result and modular zone structure derived from this room setup with its respective devices.
The line width between device controllers and sensors corresponds to the edge weight of the connection, reflecting the extent of the estimated primary and secondary effects.

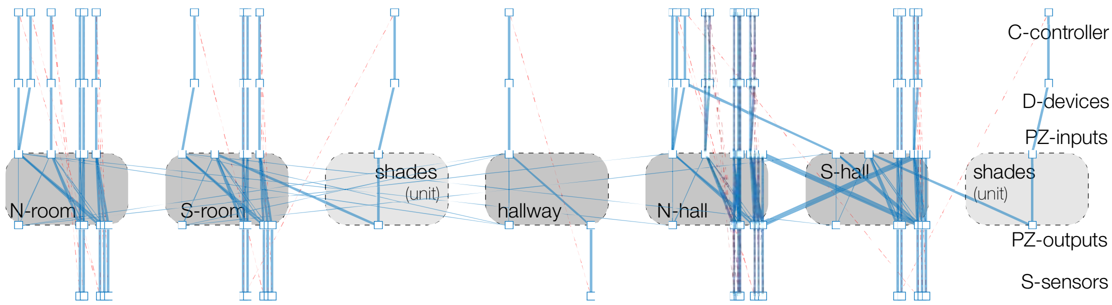


Figure 3.25 – example - control zone structure

Figure 3.27 (with the legend in figure 3.26) presents the result of the automated generative algorithm, with the additional layers of zone controllers, high-level and meta controllers.

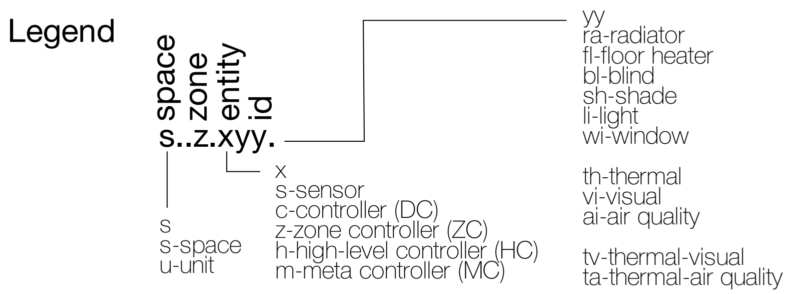


Figure 3.26 – legend for hierarchical control graph

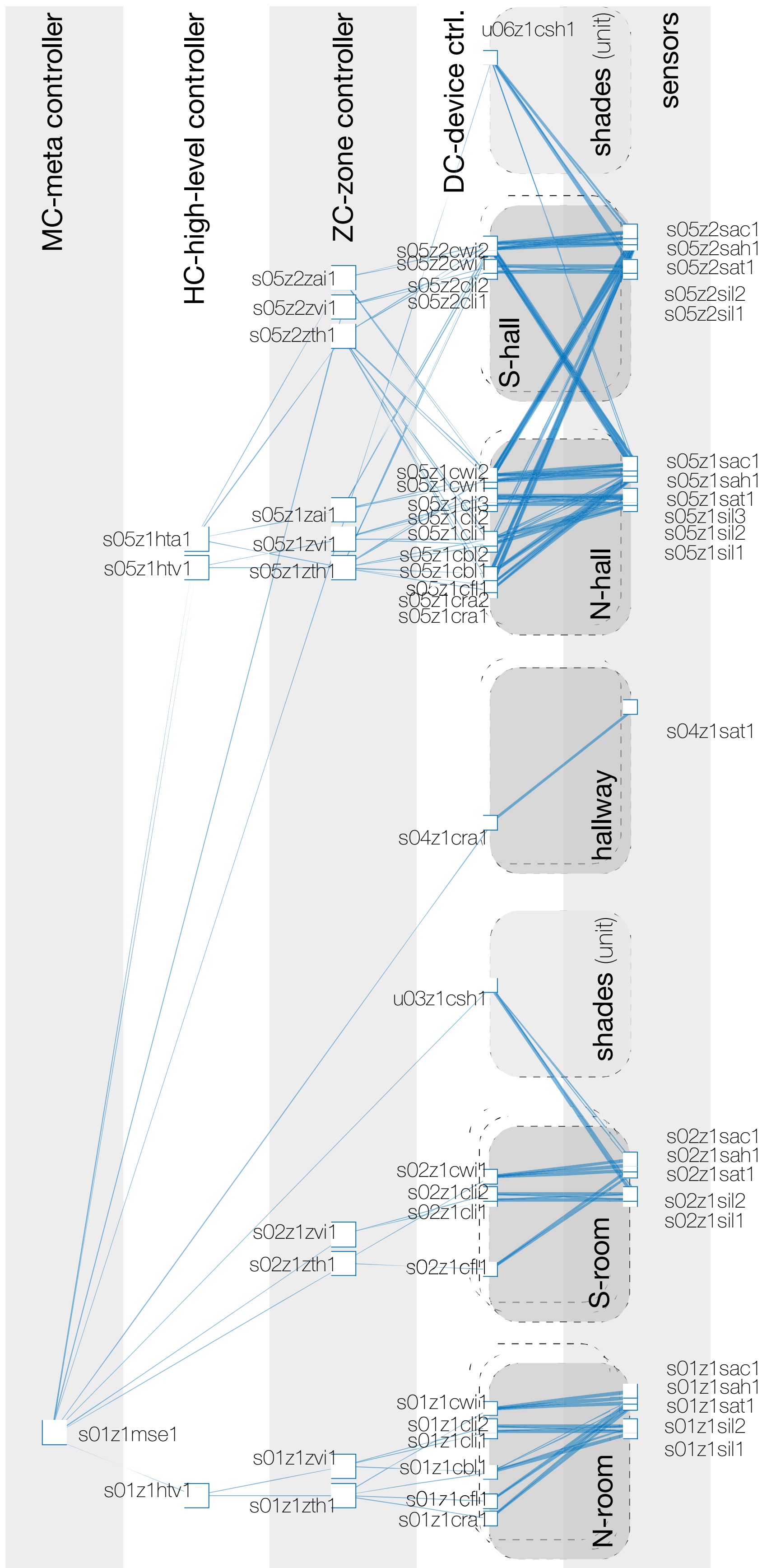


Figure 3.27 – example - hierarchical control structure

Figure 3.28 shows the structure of the final adjacency matrix (subset of complete adjacency matrix) for the example setup.

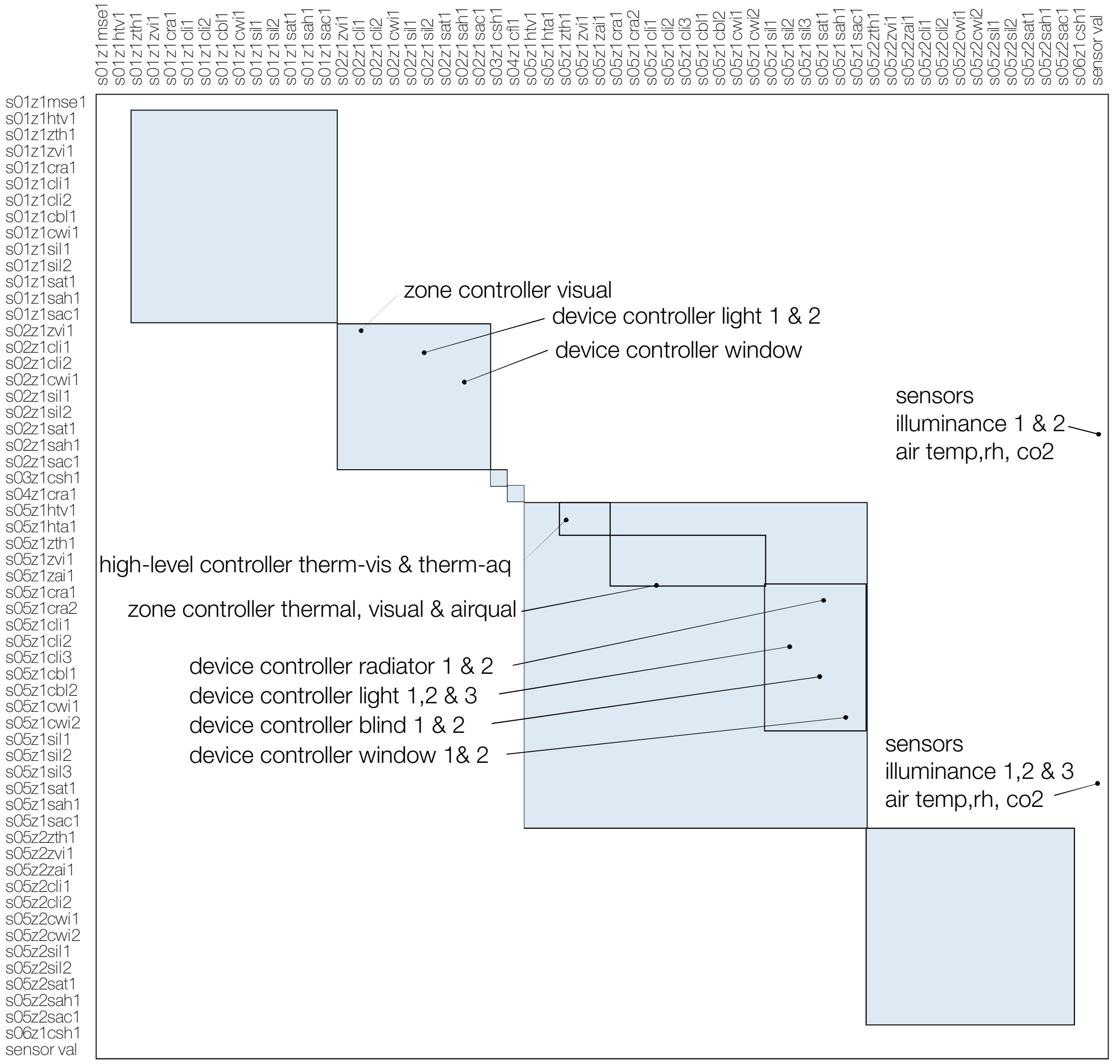


Figure 3.28 – example - adjacency matrix

3.9 Summary – control structure generation process

This chapter presented the complete process towards a hierarchical building control structure.

- Zone setup
  preparing a spatially decomposed building structure for the system/zone mapping
- System mapping
  mapping of physical system and building equipment to zones within spatial entities/aggregates
- Generation of hierarchical control structure
  a rule-based procedure for the definition of the higher hierarchical levels of a multi-level control logic scheme and the assignment of the coordination tasks
- Reduction of complexity
  intermediate process steps to cluster for space characteristics and geometry relations and to reduce systems adjacency matrix complexity by eliminating unused nodes and weak effect paths

The automated rule-based generation process steps towards a multi-level hierarchical control structure was presented in detail and the generation of the coordinating control functions in respective hierarchy layers was derived. By the applied generation principles, the process is convergent. The system representation in form of an adjacency matrix provides scalability through matrix algorithms and is suitable for a large number of nodes and edges. The presented generation process is scalable to big and complex building structures.

Figure 3.29 gives a complete view of the hierarchical aspects (spatial hierarchy and control hierarchy). It links the spatial decomposition with the zone concept and the generation of the hierarchical control structure.

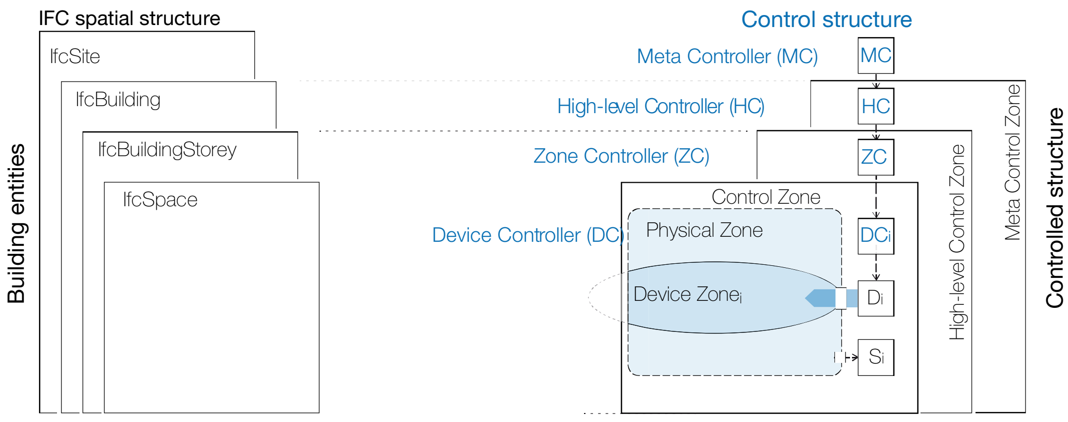


Figure 3.29 – process, from spatial structure to control structure

4 Discussion & Results

4.1 Conceptual control model

The derived conceptual model describes the system and control context and encompasses the essential relational characteristics of the system. The system mapping with its description of the manifold interrelated dynamic systems provides a consistent ground for the building system design. The developed hierarchical control structure for complex building systems constitutes a basis for a system- and project documentation; the comprehensible and transparent approach enhances the understanding communication between participating engineering domains.

The model covers the essential relations of dynamic effects of the buildings systems. The structural aspect provides a concept for the selection and simulation setup of control algorithm options. The model is comprehensive and can serve as structural basis for the specification of the control system.

The benefits of the building's control conceptual model in terms of Robinson (Robinson et al. 2015) are that it:

- minimizes the likelihood of incomplete, unclear, inconsistent requirements
- facilitates and guides the development by expressing the modeling objectives, and model/system inputs and outputs
- supports the documentation of the controlled and control system
- guides the specification and the development of control/system equipment
- provides basis for a verification and validation process of the model, simulation and system design

The structural control hierarchy scheme does not link to a specific hardware concept, nor does the control scheme or controller nodes refer to specified types or algorithms but the model represents a structural framework for control semantics.

For the building system design and the building performance simulation workflow the derived conceptual model supports the model abstraction, facilitates the prioritization of control actions and -effects, and helps to reduce the model complexity by eliminating negligible action-effect relations (Robinson et al. 2015). The activity of establishing a conceptual model goes beyond the planning and construction phase of a building. Changes during the utilization phase can have a decisive impact on the dynamic relationship of control elements and controlled systems.

4.2 System-, process- and control relevant topics

4.2.1 System topics

Lighting

The importance of the quality of lighting and the relevance of daylight for the well-being and productivity underlines the importance of lighting control.

Lighting - dynamics

In control terms and in the context of building control 'light' as actuating variable displays very special characteristics.
The instantaneousness of the dynamics of light as actuating variable leads to the time constant of the illuminance system response being basically zero with an only negligible reaction time of the lighting controller itself. In a cascaded or hierarchical control setup, the dynamics characteristic is only influenced by the dynamic response of the higher-level control circuits.

With the immediate response, and without storage or inertia effects, control strategies cannot improve the system (e.g. energy consumption) by better managing the dynamics of lighting.

Lighting - secondary effects

With the widespread employment of LED lighting technology, the secondary effect of a thermal impact affecting room temperature (and relative humidity) is becoming less important. The residual thermal energy impact could be treated as a constant or schedule-based offset, based on occupancy or equipment.

These two effects,
- reaching the reference value without delay, and
- reassignment of secondary effects

allow to view lighting control as a simple and immediate control to maintain a desired illuminance level.

Lighting control

Halonen (Halonen et al. eds 2010) categorizes three lighting control levels:

- control of artificial lighting alone
- control of artificial lighting considering parameters as daylight, occupancy, etc.
- control of artificial lighting under parameters as daylight and coordinating with other elements as shades, blinds, louvres, all the way to HVAC systems.

In the derived multi-level control structure, all three levels can be realized, depending on the finally implemented control strategies. The first two levels of lighting control do not require a link to a coordinating controller. The third level corresponds to the thesis' objective to establish a control structure coordinating all interrelated devices and systems.

For lighting, the priority is to provide as much daylight as possible, but to prevent ramifications as glare effects (direct glare, reflected glare) or thermal effects as potential overheating due to irradiation. The more daylight available, the less energy consumption for the artificial lighting. The artificial lighting provides the necessary illuminance levels in case of insufficient irradiation or in areas of reduced daylight factor. Lighting control maintains the stipulated illuminance level in the designated measuring areas/planes/points, regardless of the

- intensity (weather impact, direct/indirect irradiation) and the
- direction of incoming daylight irradiation (angle of incidence, date and time depending) and
- changes of the interior room setting (reflections).

If daylight is considered the priority source of lighting, artificial lighting represents a secondary lighting source and is supplying just enough light to bring the illuminance level to a desired level.

In such case, the energy demand level of the necessary artificial lighting becomes a function of:

- direct/indirect irradiation (measured, forecasted)
- space internal reflection setup (walls, furniture, etc. – unknown but past values available)

and of parameters, accessible in a geometrical context and calculations:

- angle of incidence is a geometric function of building location and orientation of the window, calendar day and time of the day (known)
- luminous flux (irradiation) through windows or glass facades, function of direct and indirect irradiation (weather situation, measured) and angle of incidence of direct

irradiation (known),

- attenuation factor of shades (internal or external) or louvres– specified or measurable characteristic, function of blinds setting and angle of irradiation incidence.

These relations together with weather/irradiation forecasts allow to forecast the energy demand for the additionally necessary artificial lighting.
be completely separated from the control systems in the hierarchical structure.

This can be of specific importance in context with predictive control as the artificial lighting states could be eliminated from the underlying model description. This reduction of system states could reduce the MPC's computational load or allow more extensive optimization algorithms.

The short reaction time characteristics make the lighting system a time- or dynamic priority control system. Without back effects to other control systems, lighting control could

Acoustics

Acoustic comfort related aspects rely largely on geometry, material properties and disturbance parameters as occupancy related and external noise sources.
Sources from within the building and its systems are accessible for control, or for limiting them to be more precise. Such controllable noise sources include active devices as fans or HVAC ducts, mechanical ventilation and other noise produced by building equipment.

Acoustic parameters can be influenced through e.g. doors and windows, which represent controllable attenuators for noise propagation. Continuous operation of opening/closing doors and windows to correct for disturbance noise, does not seem practical, especially in view of potential 'overcorrecting' for sudden, short-lasting and lagless noise impact.

Except for potential noise cancelling systems, there are no devices to actively interact with the physical system and to control noise and acoustic comfort parameters.
Currently there is only limited equipment available to passively control these acoustical parameters (e.g. shades with acoustic noise-reducing effects).

Acoustics - dynamics

The propagation dynamics of noise has similar characteristics as for light. It shows instantaneous effect, basically without any lagging dynamic effects. With these immediate effects, acoustic control also would have dynamic priority. For building control, they can also be interpreted as limiting factors for the manipulated variables as window/door opening position. The acoustical aspects can thus be integrated by specifying limits to the range of actuator actions, e.g. by limiting the max opening of windows as function of predicted external noise levels or limiting the maximum airflow for mechanical venting.

Acoustics - conceptual fit

The underlying concepts in the form of effect-based structural views allow to add acoustical effects to the zone concept and the hierarchical control with its comfort type related coordination levels. It does not contradict with any of the derived zone concepts or presented methods all the way to the generation of the hierarchical control structure.

It is easily possible to integrate the effects of acoustical impact if deemed necessary. There is no contradiction with any of the derived zone concepts or presented mapping. And it fits seemingly with the project concept, all the way to the generation of the hierarchical control structure. Figure 4.1 shows where and how the acoustical impact would enter the zone concept (physical zone).

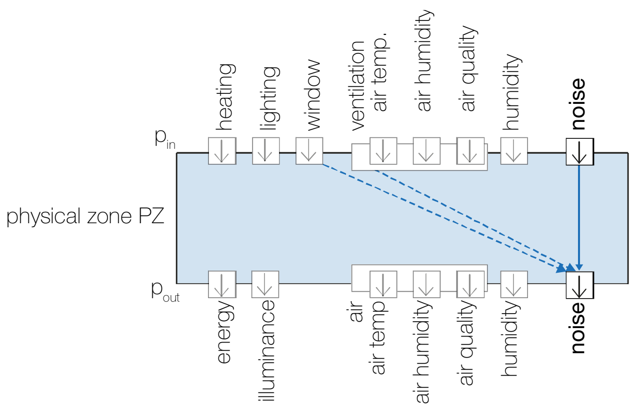


Figure 4.1 – physical zone with acoustical control

Natural venting

Apart from providing fresh air and external CO_2 levels, natural venting can help to significantly reduce energy consumption for cooling of buildings.

The driving factors are pressure differential across the building caused by wind exposure and temperature difference between zones/spaces. The flow can be controlled via the pressure loss coefficient defined by e.g. the opening position of doors (airflow resistance of the opening). In case the pressure- or temperature difference parameter is zero, there is no natural ventilation effect (only static air mixing across the opening), regardless of the position of the door or window.

A venting effect can be represented by linking of physical zones, a device as e.g. a door would represent such a link.

Control of openings cannot be implemented in the form of device controllers and devices but can be implemented as control unit with variable transfer edge weights. The effect of a door/window is a nonlinear multiplicative functional relation of the pressure/temperature difference and the door/window position. The pressure and temperature levels are defining the boundary conditions for the range of the control effect, the position is changing the flow within this range.

Coupled thermal and humidity effects

With the relative humidity as function of the temperature (and the pressure) within the physical system, the two control parameters 'temperature' and 'relative humidity' represent a highly coupled system, linked by thermodynamic laws. The system corresponds to a strongly coupled MIMO system with thermal energy and humidity as inputs and air temperature and relative humidity as output or controlled variables.

For HVAC equipment the control of these parameters is done within the HVAC control units (CU) and air with required properties (temperature, relative humidity) is delivered to the control zones (rooms/spaces).

For the system mapping and subsequently for the control structure the consequence of this highly coupled system is that any device feeding thermal energy to the physical system affects not only the air temperature but also the relative humidity. There are only few devices actively affecting the humidity within a physical zone other than HVAC control units, e.g. humidifiers and dehumidifiers; with changing the humidity content in the air these devices also directly affect the zone's air temperature.

State-space description, model identification

Transfer to state space description

The structural system relations, as described by the adjacency matrix reflect the system with its cause/effect relations. Under certain assumptions, the inherent system structure can be transferred to a state space system description. Non-zero adjacency matrix cells represent a dynamic response/transfer function between the two adjacent nodes. If the system order of that dynamic transfer function can be assumed, an approximate system equivalent in a state space system structure can be derived.

Model identification

Such state space structure, however, is not an equivalent of a white box model (structure of real system is known), but an approximation based on the system order assumption. Nevertheless, such state space structure model could serve as a grey box model for further parameter- or model identification steps.

Model based control

Model for model-based control

In case the identified system model has shown fitting system dynamics and passed a validation and verification process, for steady state- and satisfactory prediction properties, the model can be used as dynamic system model for a model predictive control algorithm (Privara et al. 2013).

Model reduction

A further application of a validated and verified grey box state space model are mathematical model reduction approaches. These methods applied on state space system descriptions aim to reduce the number of states. The reduced model yields comparable dynamic system response to the variables of the real system. Such reduced models are preferred prediction models for model-based control, as the numerical effort of these control algorithms goes up considerably with the number of predicted states.

4.2.2 Process topics

Graph edge weights

As described in chapter 'physical zone', the systems graph description can hold information on estimated (relative) effect attenuation for the dynamic response of the system (e.g. similar to Bode-diagram attenuation). This information can be assigned to the graph edges connecting the input ports and output terminals of the physical zone. These attenuation factors ($0 \leq$ attenuation ≤ 1) lead to reduced (multiplicative) effect magnitude along the effect path, the more attenuated paths segments within physical zones are passed.

Initial weight values are rather rough estimates. Refined estimates can be derived from simulations. On the other hand, the simulations can revert to the structure of the presented system mapping.

Simulations with very simplified models have shown similar results to Figueiredo (Figueiredo and Sa da Costa 2012), stating that the interrelated effects between adjacent rooms across common walls are of relatively small magnitude. The big time constants of walls together with a sinusoidal temperature of the active/transmitting room lead to even stronger attenuation effects. Applying a sinusoidal cycle of 1/day, the transmission effect is drastically reduced. Such test frequency is characteristic for building cycles, as all major external impacts (weather, irradiation, occupancy, etc.) change with that cycle period (Pfafferott et al. 2005). Any cross effects initiated with higher frequencies (e.g. control switching for thermal control, pulse width modulation control) lead to an elimination of the already low cross-effect on adjacent rooms.

Relative energy/mass impact

The system description by adjacency matrices also allows to assign relative weights representing the magnitude of the devices impact effect. E.g. a device impacting the system thermally with 100W will have different effects than a device with 1000W. To stay in line with assigned edge weights, such relative weights can be assigned to the graph's edges between the devices and their respective input port to the physical zone. A normalization of the device effect magnitudes (e.g. W/m^2) can get involved, especially when several zones are linked.

Default weights

Nonetheless, the system mapping and control structure generation process can also be done without assigning any attenuation factors and using a default value of 1 (full effect propagation). This also results in a valid structural model representing the building's relational system and can be used to derive a hierarchical control structure. In this case the reduction step R3 does not have any effect and is omitted. The resulting conceptual model still can serve as a basis for the control simulation or for system identification.

Connex to simulation

The presented methods relate to building simulation in different ways. E.g. simulations on reduced detail level can provide valuable estimates for primary and secondary effect impact magnitude (Gladt 2014) and a frequency analysis of system responses.

In turn the presented method provides an assessment method to qualify control structure parameters by impact ranking (Pareto analysis). By concentrating on control variables with significant impact, the complexity and computational load of control simulations for complete building setups can be reduced. Control effects with low impact magnitude can be identified and excluded and treated as disturbance variables.

The conceptual models also allow analysis for controllability, which is important for investigations on operation modes in case of equipment failure (e.g. graceful degradation). The model can indicate characteristic building setups for simulation under varying structural situations (e.g. doors, natural ventilation, …) and supports systematic simulation composition in case of devices spanning across multiple zones (e.g. external blinds or louvers).

As further energy demand savings are expected in context with exploiting thermal mass effects, simulations emphasizing such conditions are of special interest. Simulations in this context are particularly interesting for studies on predictive control algorithms and for decoupling and energy peak shifting techniques.

The resulting control hierarchy and its flexible node definition allows the simulation of hierarchical control structures of complex control algorithms, namely model based, predictive control and multi-objective optimization e.g. economic-, hierarchical and stochastic MPC.

The structural information of the system description in form of an adjacency matrix can serve as basis for grey-box identification processes and state space description of the system. Mathematical models derived from such model identification are required for model-based control algorithms. They are also the basis for mathematical model reduction methods to reduce the order of the system model. This approach can be a decisive advantage, especially for complex control algorithms and for simulations with high computational requirements,.

Impact estimation of relevant building changes

Structural changes in the building configuration can change the effect propagation within and between zones and thus alter the structural model significantly (e.g. air exchange through open doors between control zones). Evaluations of such changes in context of a control structure derived for other setups may be helpful in the system development and specification.
The model can indicate characteristic building setups for simulation under varying structural situations (e.g. doors, natural ventilation, …) and supports the simulation composition in case of devices spanning across multiple zones (e.g. external blinds or louvers).

4.2.3 Control topics

Manual control impact

The conceptual model also supports studies on effects caused by manual operations. Manual input to the control and system structure can be integrated at either the device level or at the controller level by setting the command/set variable. With the control model the effect of such interaction can be tracked to directly/indirectly affected output ports. This can be important when manual operation has to take over in case of equipment malfunction.

Controllability

Usually the controllability of a system is checked with the state space description of the control system. The controllability can also be checked with the control structure model. If there is an effect path from the controller to the systems measured output (sensor at output port of the physical zone) this parameter is controllable by the respective controller.
As the graphs get more involved and graphical display too confusing. The graphs and their description in form of adjacency matrices however are suitable for algorithmic searches of path connections between two points. With these path search algorithms automated check for controllability can be performed.

In case of a controller failure, an interaction via a secondary effect paths might be useful. Controlling via secondary effects is an uncommon but possible setup and can be analyzed with the structural model.

4.3 Conclusion

The thesis has demonstrated the feasibility of an automatable generation process for a building control structure in a classical closed-loop control approach.

The selected structural approach permits to map the buildings systems and to follow the impact-effect description throughout the process. Intermediate steps keep the process transparent and comprehensible for all involved domains. The systematic method provides domains specific views of system and control relevant characteristics.

The process is deployable within the BIM framework and its workflows. By accessing building models represented in the IFC data structure, users are not burdened with data inconsistency or potential incompatibilities of a new data format.

The structural approach involves a strictly modular concept; this includes the developed zone concept and control and system relevant elements for the mapping process. The hierarchical concept with control circuits and controller elements is consistent with the modular principle.

The automated rule-based generation process towards a multi-level hierarchical control structure is based on the description of a directed graph in form of its adjacency matrix. Matrix calculations are suitable for automated processing, and the involved operations can be handled up to considerable matrix dimensions. The process thus remains scalable and can be applied to large size buildings with high complexity of their systems.

The structural control hierarchy scheme does not link to a network topology or hardware concept. Controllers do not represent a specific product, algorithm or functionality but represent structural nodes as containers for any type of controlling algorithm or control semantics. This allows flexibility for the selection and optimization of control algorithms.

Outlook

Further developments in technology and the commitment for further optimization of buildings (energy, comfort) offers a wide field for research and will continue to drive the development of building automation and control strategies.

Continuing work concentrates on linking the control structure model into the domains of simulation, model identification, and support tools for building automation as well as into system engineering and its models, as e.g. automated generation e.g SysML model descriptions.

Index

Abbreviations

AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
BA	Building Automation
BACS	Building Automation Control Systems
bdd	block definition diagram (SysML)
BIM	Building Information Modeling
CFD	Computerized Fluid Dynamics
DC	Device Controller
DZ	Device Zone
HC	High-level Controller
HVAC	Heating, Ventilation and Air Conditioning
ibd	internal block diagram (SysML)
IFC	Industry Foundation Classes
IT	Information Technology
MBSE	Model Based System Engineering
MC	Meta Controller
MEP	Mechanical, Electrical and Plumbing
MIMO	Multiple Input - Multiple Output System
MPC	Model Predictive Control
par	parametric diagram (SysML)
PZ	Physical Zone
SCADA	Supervisory Control and Data Acquisition
SE	System Engineering
SIMO	Single Input - Multiple Output System
SISO	Single Input - Single Output System
SysML	System Modeling Language
UML	Unified Modeling Language
ZC	Zone Controller

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Appendix

Visualizations help to effectively communicate a system's structure and to facilitate a common system understanding; and close the gap between domains and their respective views of a building's control system.
The presented control path views show the conceptual control structure model and examples of evaluations to enhance a common inter-domain understanding.

Evaluation of the control paths, all the way to the effect on the controlled variable, provides information on whether control nodes can directly assume auxiliary control functionality for a specific controlled variable or whether this has an impact on the controller design and specification. The conceptual model allows analysis on operation modes in case of equipment failure (e.g. graceful degradation).

Example

A floor of an office building serves as an example case (same setup as described in 'example' chapter 3.8). Figure A.1 presents the floor plan with 18 rooms. 8 offices are oriented towards the north and south respectively, 2 open plan offices extend from the southern to the northern facade. Due to the size and the different external impact the open-plan offices are split into two physical zones.

The layout with its setup and employed devices allows a reduction by clustering. This leads to 4 room types and 5 zones, the northern and southern offices, the hallway and the open-plan office with its two internal zones (see figure A.1 bottom).

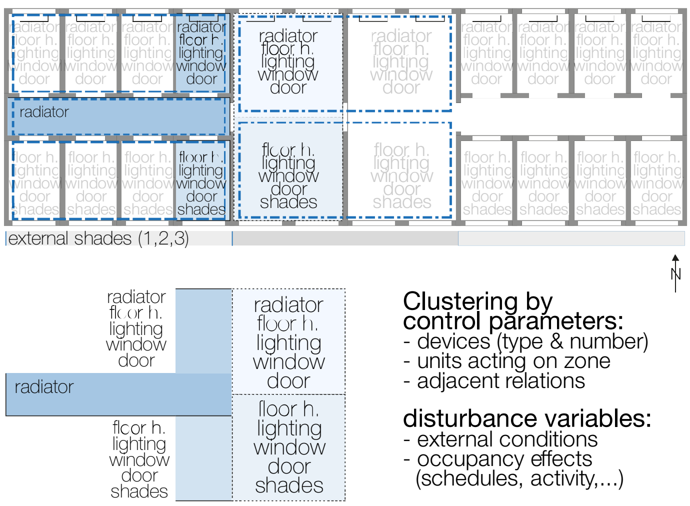


Figure A.1 – Example, floor plan

Figure A.2 shows the mapping result and modular zone structure derived from this room setup with its respective devices.

The line width between device controllers and sensors corresponds to the edge weight of the connection, reflecting the extent of the estimated primary and secondary effects.

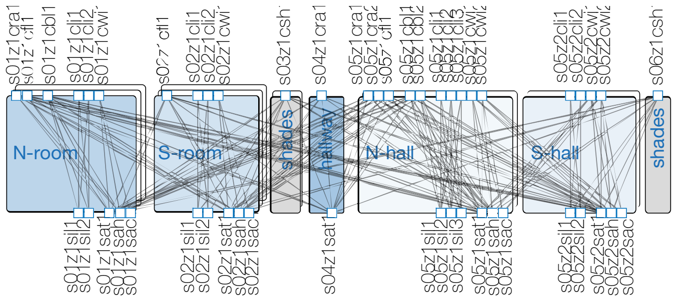


Figure A.2 – Physical effect relations

Figure A.3 (with the legend in figure A.4) presents the result of the control structure generation algorithm, with the additional coordination/control layers of zone controllers (ZC), high-level (HC) and meta controllers (MC).
To keep all systems relations, the generation process of the control structure omitted step R3 – elimination of low-level effect paths.

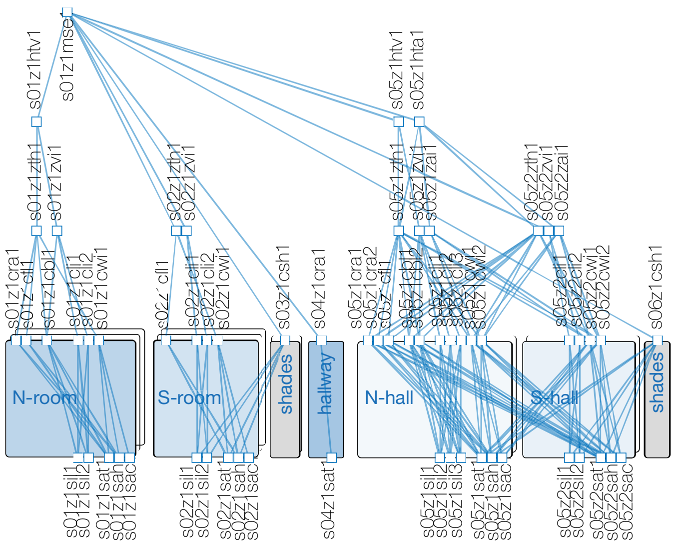


Figure A.3 – Control structure

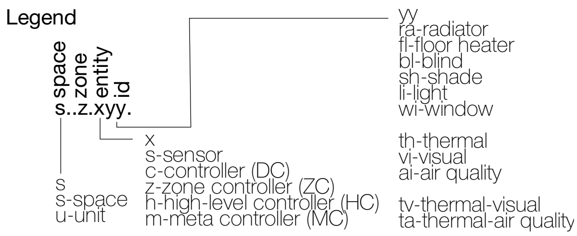


Figure A.4 – Example, legend

Control path views

These graphs represent the information-, energy- or mass (fluid) paths in a control network, in this case within a building and its control system. The edges connecting the controller nodes (controlling system) represent information flow, whereas the edges within the physical systems (controlled system) are of energy and/or mass flow type.
The underlying graph is a directed graph with the connections leading from the top to the bottom. The feedback signals (sensor feedback) are not shown in the graphs, the measurement information is considered to be made available to all control nodes through a network system.

The example structure of the building is analyzed in two ways:

- following the control action paths, from controller (via the device) to a sensor, representing a measured output variable
- back tracking the effect path, from a sensor node back to controller nodes having an impact on the respective output state (sensor value)

Control paths: controller to outputs

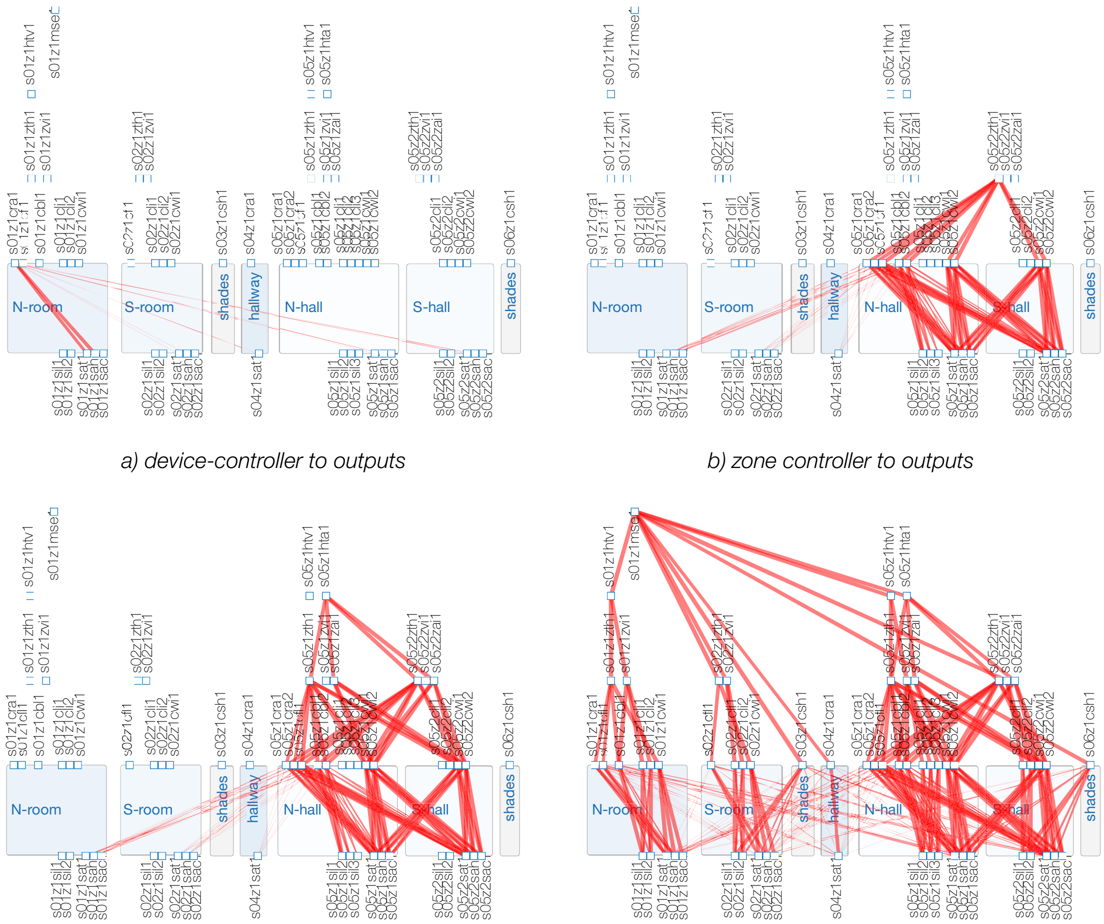
In this case the source node is a controller node and, due to the structure of the directed graph, all 'other' reachable nodes are either other controllers down the control hierarchy structure or all affected output nodes.

For the control structure as well as for the physical structure (controlled system), the total edge weight (multiplicative edge distance) is the product of the edges passed.
The shortest path is indicating the path with the biggest impact from to a controller node to any other reachable node, especially the output nodes. In case several paths have the same weight, only one will be indicated.

However, the objective of this specific case is to show all control action paths from a controller to an output, not only the shortest one. A routine has been adapted (Kearney 2014) to return all available paths together with their total weights (product of edges).

Figure A.5 shows samples of such control path views. Subfigure a) shows the effect paths from a device controller (device: radiator in zone 1, N-room). A more complex effect path structure is shown in b) with a thermal zone controller (ZC) as source (thermal zone controller, subzone within open-plan office, S-hall); this view is further extended to c), the thermal/visual High-level controller (HC).

The view d) shows the view with the meta controller (MC) as source node. This result is trivial as by definition, the meta controller as highest control instance has an impact to all outputs via its sub-controllers within the hierarchy. The shown effect paths coincide with the control structure as shown in figure A.3.



a) device-controller to outputs

b) zone controller to outputs

c) high-level controller to outputs

d) meta controller to outputs

Figure A.5 – Control path views

Effect backtracking – output to controller

For some system examinations and evaluations, it is of importance to analyze for the controlling/impact sources for a specific system state (sensor node).

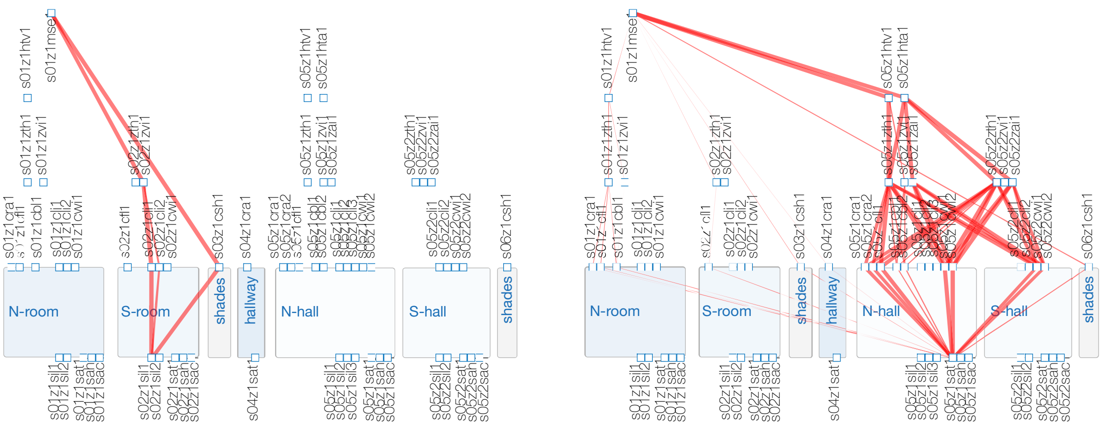
To find the respective effect paths in the directed graph, it is necessary to backtrack the edges coming into an output node against the signal and effect path direction.

The backtracking can be performed in two ways:

- Reversing the direction in the system's adjacency matrix by mirroring/flipping the matrix over its diagonal and then perform a search for all paths from an output node to all controller nodes (as explained before)
- Applying the control action path search in the direction of the directed graph (as described above), iterating through all controllers and retaining the connection paths leading to the specified output node.

Figure A.6 a) shows an output node (illuminance) impacted via three device controllers (device controller & device), one via the illumination control and lighting and the other via the control of the external shades and the third via the other illumination equipment.

Subgraph b) shows the situation for a thermal output (zone temperature); this represents a system state (output node) with multiple incoming effect paths (multiple controllers impacting); main effects are cross effects of the open-plan office, consisting of two zones, with each of the two zones being affected by multiple devices.



a) illuminance output, S-room　　*b) thermal output of open-plan office, subzone 1*

Figure A.6 – Example, control structure

Impact views with relevant building changes

In this example configuration, effect path variations are introduced by changes of the underlying system interrelation (linking edge weights) due to the opening status of doors or openings between rooms. Figure A.7 shows the considered door/opening functions.

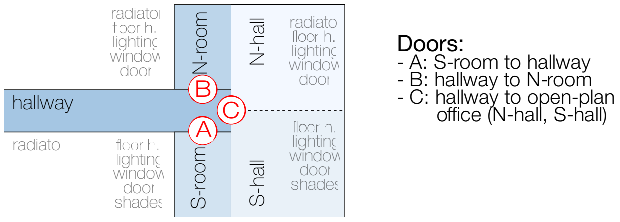
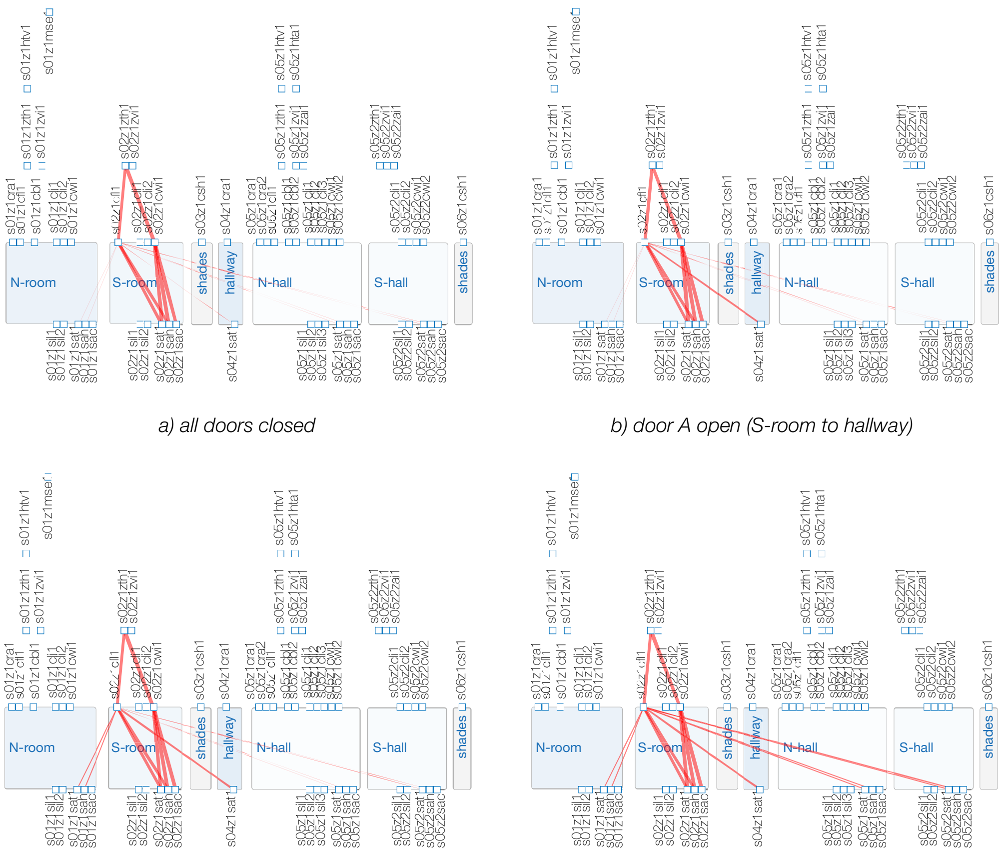


Figure A.7 – Door configuration

Note: as this view reflects the clustered/reduced floor geometry, the sample doors (A, B and C) always refer to all doors of a kind. E.g. door A refers to all doors between all southern rooms and the hallways.

Control paths: controller to outputs

Figure A.8 shows control paths to the thermal zone controller for the southern room zone with different door settings (zone cross relation settings).



a) all doors closed

b) door A open (S-room to hallway)

c) doors A & B open (S-room to hallway & N-room)

d) all doors open (A, B, C)

Figure A.8 – Door impact, control path view

Figure A.8 a) represents the controller effect paths for the initial case with all doors closed, b) refers to the altered system with all doors A (S-room to hallway) being open and shows an additional effect path into the hallway.
Subfigure c) shows the same view with doors A and B open. Finally, element d) shows the effect paths from the thermal zone controller to the affected outputs for all three door types in open condition.

Effect backtracking – output to controller

Figure A.9 shows the views of a selected output state (air temperature in zone 2, S-room) and indicates which controllers are having an impact on the selected output node (back-tracking view).
As before, subfigure a) represents the effect paths for the initial case with all doors closed, b) refers to the altered system with open doors A. Figure c) shows the same view with doors A and B open and subfigure d) shows the impact paths for all three door types in open condition, from various controllers on the selected output (air temperature in zone 2, S-room).

These graphs show the changing complexity of the control structure when the underlying system changes during the utilization phase or due to occupancy actions.

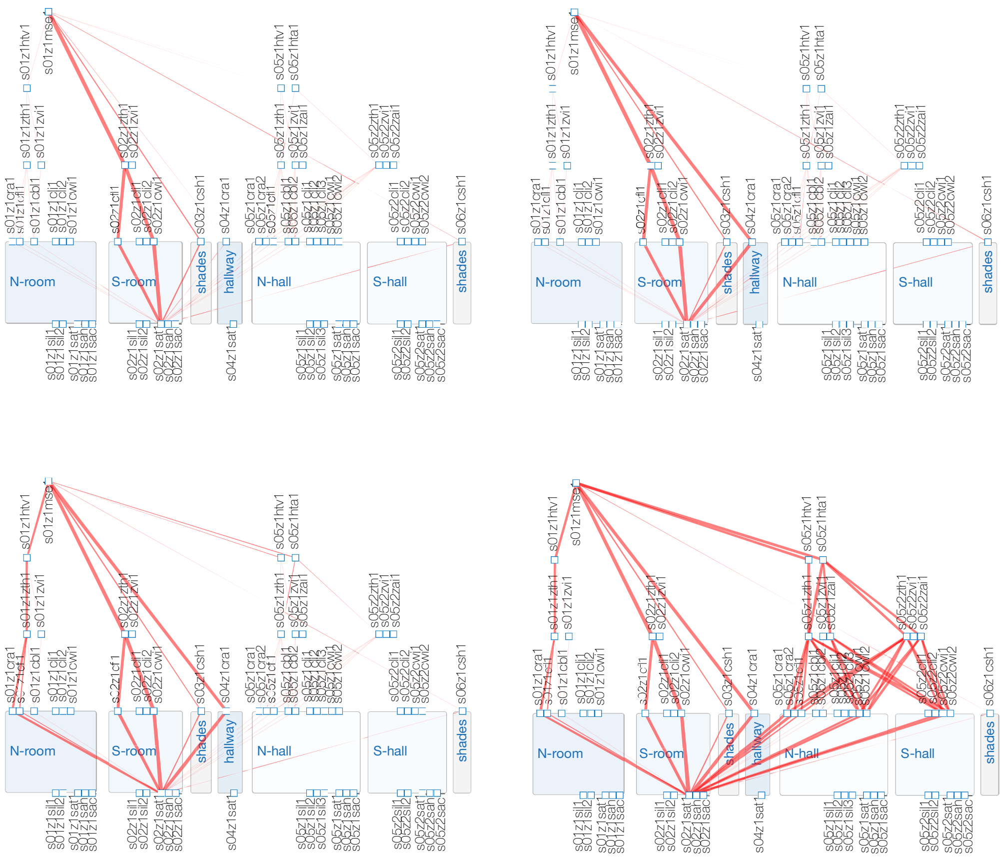


Figure A.9 – Door impact, control path backtracking

Curriculum Vitae – Norbert Sterl

Professional Background

2016-18	Project related work Associate Expert, special projects at expert's offices Sachverständigenbüro Soucek KG and EXPERT TRADE & SERVICES Ltd.
1999-13	Business Development Manager, Global Product Manager, Manager Technical Marcom; TYCO ELECTRONICS AUSTRIA GmbH, Business group relay products
1997	Director; SCHRACK COMPOSANTS ELECTROMECANIQUES S.A.
1995-99	Head of departments 'Strategic Business Development', 'Projects & Innovations' and Marketing Communications; EH-SCHRACK COMPONENTS AG a Siemens Company
1993-95	Product Marketing Manager, Head of 'Marketing Services'; EH-SCHRACK COMPONENTS AG
1992-93	Head of department 'Security Engineering'; STEYR-DAIMLER-PUCH SPEZIALFAHRZEUG AG
1992	Business Consultant
1986-91	Export Manager and Head of Marketing Services (89-91), Assistant Product Manager (86-89); EH-SCHRACK COMPONENTS AG
1983-86	Development Engineer and Project Manager; VOEST-ALPINE-FRIEDMANN GmbH., VOEST AUTOMOTIVE
1981-82	Teaching Assistant in Electrical Engineering, DREXEL University, Philadelphia, PA, USA
1975-79	Internship positions in Austria, Switzerland and England

Educational Background

2016-	PhD program at the TU-Wien
2013-16	Graduated in Master program 'Building Science & Technology', TU-Wien
1989	Graduated in Industrial Management/Economical and Social Sciences at the Vienna University of Economics and Business
1981-82	Fulbright-scholarship at Drexel University, Philadelphia, PA, USA
1982	Graduated Engineer in Mechanical and Electrical Engineering at the TU-Wien

Publications

2018	'System Mapping and Generative Hierarchical Zone Control Structure for a Scalable Building Control Logic', Bausim 2018, Karlsruhe, Germany
2016	'Consideration of Heating Elements' Behaviour in a Co-simulation Setting using Model Predictive Control', BauSim 2016, Dresden, Germany
2016	'Exploring the Energy Saving Potential of Model-Predictive Controls via Dynamic Co-Simulation', Clima 2016, Aalborg, Denmark
1997	Technical book on relay technology 'Power Relays', ISBN 3-9500637-0-6