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# Interference Patterns in Adaption Mechanisms: Interleaving of self-organising meso-level structuration algorithms with introspective self-evaluation algorithms

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*To Livia*

## Abstract

Increasing complexity and unpredictability emerge in many modern systems, raising the need for suitable paradigms and concepts. Organic Computing principles like self-organisation and decentralised decision making are incorporated in adaptation mechanisms, reacting to changes in the environment by adapting their structures or behaviour. Due to the high complexity and scale, these systems often constitute System of Systems with adaptation mechanisms operating on multiple system levels. In one part of this Thesis, interferences due to two interleaving adaptation mechanisms, affecting common structural elements, are investigated with respect to emerging patterns and impact on macro-level behaviour of a cyber-physical case study system in the power management system (PMS) domain. In the other part of this Thesis, the vital distribution component of this PMS is replaced by an agent-based allocation system, formulated as an electronic institution, whose outcome is evaluated by agents and used in the system's micro-level adaptation mechanism. While especially considering the mission-critical system nature, the agent-autonomy and degree of self-organisation is promoted through the incorporation of socio-economic principles and principles of distributive justice for common-pool resource allocation.

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# List of Abbreviations

| | |
|---|---|
| **AC** | Autonomic Computing |
| **AM** | Autonomic Manager |
| **APM** | Autonomous Power Management System |
| **AVPP** | Autonomous Virtual Power Plant |
| **CPP** | Controllable Power Plant |
| **CPR** | Common-Pool Resource |
| **CPS** | Cyber-physical System |
| **CSOP** | Combined Constraint-Satisfaction Optimisation Problem |
| **DER** | Distributed Energy Resource |
| **HiSPADA** | Hierarchical SPADA |
| **LPG** | Linear Public Goods Game |
| **LPG'** | Varied Linear Public Goods Game |
| **MAS** | Multi-Agent System |
| **OC** | Organic Computing |
| **PMS** | Power Management System |
| **PPP** | Physical Power Plant |
| **PSO** | Particle Swarm Optimization |
| **SoS** | System of Systems |
| **SPADA** | Set Partitioning Algorithm for Distributed Agents |
| **SPP** | Stochastic Power Plant |

| | |
|---|---|
| **SuOC** | System under Observation and Control |
| **TEG** | Trusted Energy Grid |
| **TEMAS** | Trust-Enabling Multi-Agent System |
| **VPP** | Virtual Power Plant |

# Chapter 1

# Introduction, Goals and Motivation

To face the problem of increasing complexity and unpredictability emerging in many of today's technical systems, Organic Computing (OC) principles like self-organisation and decentralised decision making are used in adaptation mechanisms, controlling those systems and reacting to changes in the environment or violations of their constraints by adapting their structures or behaviour. Such systems are conveniently represented by Multi-Agent Systems (MAS), where actors or agents autonomously pursue their goals and make decisions based on their limited, local knowledge.

Distribution is a common inherent element in many of these systems, be it the distribution of resources, mandatory for the operation of the participating agents, e.g., energy or computing power in ad-hoc sensor networks and peer-to-peer networks or distribution in a wide-range of MAS-modelled real-world infrastructure systems, like Smart-Grids or Power Management Systems (PMS). In heterogeneous MAS, rational agents, like human actors, behave selfishly, maximising their individual payoff, which leads to depletion of resources in an un- or unsuitably regulated distribution scenario, as stated by the Tragedy of the Commons. To ensure enduring operation of these systems, distribution mechanisms, circumventing depletion of the resources and consequent instabilities, are of high importance, especially in mission-critical infrastructure systems, where the consequences of resource depletion or instability severely threaten their system goals.

In this work, socio-economic principles are applied to a PMS, promoting its stability through the incorporation of endurance-promoting socio-economic principles within its distribution component. An allocation mechanism incorporating fairness as essential concept in distributional justice is presented, as is the adoption of other principles, identified as necessary for an institution to endure by Elinor Ostrom, like the holistic member-participation in rule and decision making and situation-dependent rule selection.

Complex systems often reveal System of Systems (SoS) properties such as a structure subdividing in different levels of abstraction or scopes which allows for a complexity-reduction at each level. Each scope therefore deals with scope-specific properties, structure, elements and goals of the system and thus commonly several adaptation mechanisms are implemented, each reflecting and working on one structural level. As these mechanisms however work on the same SoS, structural changes on one level may also influence the structure of another, especially at their common boundaries, and may trigger the need for action on other levels, i.e., trigger their adaptation mechanism.
These interferences, caused by the interleaving of adaptation mechanisms, affecting common structural elements on different abstraction levels, may influence the SoS's macro-level behaviour which is subject to user requirements and may circumvent the desired system behaviour e.g., by interfering with desired emergent effects, the system is designed to produce (controlled emergence).
In the PMS case study, used in this work, the interference of several concurrently active self-organisation adaptation mechanisms is investigated. The focus of this investigation is laid on the mutual influence of the structuration algorithms and the organisational fair self-organised distribution mechanism, how patterns emerge in forming enduring and fair institutions and how the resulting self-organising hierarchy, based on these interactions, influences the overall macro-level system behaviour in terms of stability.

This Thesis is structured as follows: In the next chapter, the case study, serving as a basis for the work and investigations of this Thesis is introduced as the Autonomous Power Management System, incorporating two self-organising adaptation mechanisms effective on multiple layers of a SoS as well as a power distribution mechanism. The latter is replaced by an allocation system based on an endurance-promoting electronic institution, whose fundamentals adoption of socio-technological principles and paradigms of distributional justice are introduced and explained through examples in Chapter 3. After the motivation for the adoption in the case study PMS is presented, the conceptual mapping of the computational justice incorporating electronic institution and the distribution component of the PMS and its realisation is elaborated in detail in Chapter 4. The implemented approach is empirically validated in Chapter 5 and used as a basis for the investigation on interferences of interleaving adaptation mechanisms, concurrently affecting common structural elements. The closing Chapter 6 summarises the approach and its evaluation as well as the investigation results and gives an outlook on further work.

# Chapter 2

# Case Study: Autonomous Power Management System using AVPP-Hierarchy constituted System of Systems

The Autonomous Power Management System (APM) is a case study in the domain of energy-management and serves as a basis for the investigations of this work. In this chapter, an introduction and brief overview over the APM is given, followed by a more-detailed description of its components, as relevant for this Thesis. In Section 2.1, an important organisational element, the Autonomous Virtual Power Plant (AVPP) which bundles power plants and allow for a complexity reduction through decomposition, is introduced, including a description of the scheduling process, which is the APM's distribution component, and a self-organised adaptation mechanism. After the incorporation of the trust concept is outlined, the APM's structuration mechanisms is described in Section 2.3, followed by an explanation of the APM's System of Systems (SoS) nature and a summary of its adaptation mechanisms, whose interference potential and thus the main analysis of this Thesis, is outlined subsequently. Lastly, related concepts to the AVPP, as well as to interferences in SoS are described in the related works section in Section 2.4.

The APM implements a decentralised control of electrical power supply, facing the rapidly growing number of decentralised power plants (e.g., small solar power plants) and the inherent challenge of adapting the power production of controllable power plants (e.g., traditional coal- or nuclear power plants) to meet the overall power demand in the power grid, regarding the uncertain production amount of stochastic producers. Deviations in demand and supply will alter the power-network's line-frequency which, leaving a certain range,

will cause both electrical consumers and producers (*load shedding*) to stop operation and may ultimately result in black-outs and thus are to be minimised to assure stable power supply. As the power-production of stochastic producers depends exclusively on weakly-predictable exogenous influences of stochastic nature like solar-radiation or wind intensity (i.e., weather factors), it is exposed to high fluctuations and thus hardly predictable and compensable. (Steghöfer & Reif 2012)
Due to the large, and growing, number of producers the power grid is to be classified as a large-scale system. It is also mission-critical, as power supply is of utmost importance for our modern society in all, private, public and industrial sectors. Beside the aforementioned network-frequency deviation, several risk factors, like failures of components, may have a severe impact on the operability of the power grid. Failures like overloading may harm both humans and electronic devices which exhibits the power grid's safety-criticality. (Anders et al. 2013)
To deal with these risks, the (macro-level) system goals are given as:

- Stability of the power grid
- Compliance to legal regulations

The APM is implemented as an application layer based on the Trusted Energy Grid (TEG), which is a reference architecture and an application-specific extension of the Trust-Enabling Multi-Agent System (TEMAS), which implements a Multi-Agent System (MAS), incorporating the trust concept. The domain model consisting of power consumers and power producers, represented as agents, and a power grid to which producers and consumers are connected, as well as abstract functions are implemented in the TEG, whereas the central concept of the APM, described in the following section, and concrete functions are implemented in the APM. (Anders et al. 2013)
As considering the software–architectural details is not necessary for this work, in the following it is abstracted and simplifyingly referred to as APM only, without further differentiating between APM, TEG and TEMAS.

## 2.1 Autonomous Virtual Power Plants

In the APM, power producers are combined in Autonomous Virtual Power Plants (AVPPs) as depicted by Anders et al. (2010). AVPPs are self-organising, dynamic containers, clustering different types of power plants, such that an overall stable production at the scope of an AVPP can be achieved. An AVPP appears as a power plant agent, representing and hiding its containing power plants from the outside. It contains Physical Power Plants (PPPs) which have to fulfil the power demand, assigned to the AVPP, by their power productions. There are two types of PPPs, as described before: Stochastic Power Plants (SPPs) produce power based on exogenous factors and are thus uncontrollable, whereas the power production of Controllable Power Plants (CPPs) is controlled. It is therefore necessary to define the desired outputs for each CPP within an AVPP for the next time steps, which is depicted as **power schedule**.

Schedules are created autonomously by an AVPP, determining a power load distribution among its CPPs within the **scheduling** process. Within the scheduling, the *residual load* is defined as the difference between the power demand, assigned to an AVPP, and the predicted power production of all SPPs within the same AVPP. The residual load is to be fulfilled by the CPPs:

$$resLoad(t) := assignedLoad(t) - \sum_{s \in SPP} predPower_s(t) =: \sum_{c \in CPP} schedPower_c(t) \tag{2.1}$$

Physical properties of the involved power plant types are approximated in respective power plant models. Scheduling-relevant model measures are minimal and maximal power output as well as power output change rate (slope rate) on the technical side and power production costs on the economic side. To create a feasible schedule for each CPP, their restrictions have to be considered, e.g., a CPP cannot arbitrarily adjust its output because of its production inertia, expressed by its slope. Due to maximum- and minimum production restrictions, there may be **violations**, in the case that the total power production capacity of an AVPP's CPPs cannot equal the AVPP's residual load. The restrictions given by the models can be formulated as constraints and will referred to as such in the following parts of this work. In the APM, solutions are currently computed by solving a Combined Constraint-Satisfaction Optimisation Problem (CSOP), resulting in an optimal production output for each CPP such that the violation of the residual load is minimised, as are the power production costs. (Steghöfer et al. n.d.)

To deal with changes by autonomously adapting to them, an AVPP changes its structure when required. To trigger an **AVPP reformation**, it monitors the CSOP-feasibility, altered by changes in demand and production predictions or potential outages of power plants, as well as violations to user-defined constraints like a desired energy sources mix, a desired trust mix or the operation within reasonable ecological and economical levels, as given as one system goal. If an AVPP is deemed unfit for purpose by its constituting power plants, it gets dissolved and recreated with a different structure by a structuration algorithm as introduced later in Section 2.3.

One major contribution of this Thesis is the formulation of the scheduling process using an allocation mechanism based on socio-economic principles promoting endurance and fairness. Based on the outcomes of the scheduling, i.e., the power schedules, each subordinated power plant will assess a satisfaction with its schedule, expressing the subjectively perceived fairness of the allocation mechanism. This fairness will then be used as a criterion to trigger a reformation of the AVPP. This allocation mechanism and its integration is explained in detail in Chapter 4, after an introduction to allocation systems in Chapter 3 is given.

## 2.2 Trustworthiness of Power Plants

Uncertainty in terms of stochastic power production prediction is a crucial factor for the application provided by the AVPPs. To handle uncertainty, a power plant's power prediction accuracy is expressed using the notion of credibility[1] and quantised through a *credibility metric*, defined within the TEG. Credibility, together with a power plant's reliability[2], which basically measures the availability of the power plant operation, i.e., on-line production time, expresses the trustworthiness of a power plant and thus incorporates the concept of trust within the APM. An AVPP's trust-value is proportional to the accuracy of its prediction and its availability, which themselves are aggregated from the power plants constituting the AVPP. Trust plays a substantial role, firstly within the formation of AVPPs, as described in the next section and secondly within the scheduling, where the dependency on untrustworthy power plants is reduced. (Anders et al. 2013)

## 2.3 Structuration and Adaptation Mechanisms

The (initial) formation of AVPPs can be formulated as a set partitioning problem. Anders et al. (2012) proposed 'a decentralized multi-agent algorithm for the set partitioning problem (SPADA)' which solves the set partitioning problem while complying with MAS-concepts like agent-autonomy and local knowledge. Set Partitioning Algorithm for Distributed Agents (SPADA) forms initial or reforms existent AVPP-formations by performing anti-clustering on the power plant agents. Using the trust values as a similarity measure, the power plant anti-clustering forms clusters, that are similar to each other (i.e., the trustworthiness of all AVPPs are similar) but consist of dissimilar power

[1]Credibility is 'the belief in the ability and willingness of a cooperation partner to participate in an interaction in a desirable manner' (Steghöfer et al. 2010, p. 66).

[2]Reliability is 'the quality of a system to remain available even under disturbances or partial failure for a specified period of time as measured quantitatively by means of guaranteed availability, mean-time between failures, or stochastically defined performance guarantees' (Steghöfer et al. 2010, p. 66).

plants (i.e., an AVPP includes dissimilar power plant types).
Agents get invitations to join an AVPP (join partition requests) and decide on their own will whether to join, striving to increase their individual benefit, thus maintaining their autonomy. They employ a fitness metric that allows the agents to measure their subjective satisfaction and form a collective opinion about the fitness for purpose of the current structure (i.e., the combination of agents within the AVPP).

### 2.3.1 AVPP-Hierarchy constituted System of Systems

Considering performance, the scalability of the scheduling is limited, as it is an NP-hard problem and requires a high amount of data to be shared. To attenuate the scalability issue, the APM implements a **System of Systems (SoS)** by introducing intermediary AVPPs, that nest and group other AVPPs and thus decompose and delegate the scheduling problem to its subsidiaries, overall forming a **hierarchical AVPP structure**.
Steghöfer et al. (2013) proposed the Hierarchical SPADA (HiSPADA) algorithm which implements a hierarchical control loop that adapts the AVPP-hierarchy. Based on application-defined constraints and scheduling duration, HiSPADA may introduce new layers as well as reorganise or dissolve existing layers. E.g., given an AVPP $f$ whose scheduling runtime exceeds a certain threshold, HiSPADA introduces a new hierarchy level by creating intermediate AVPPs, subordinated to $f$. SPADA[3] is used to repartition $f$'s former subsidiaries and assign its created partitions to $f$'s new subsidiaries. $F$'s former subsidiaries may either be PPPs or AVPPs, which in the latter case, reveals the SoS structure of nested AVPPs. While the introduction and dissolution of hierarchy levels are triggered only by runtime-threshold exceedance or lower deviation respectively, the reorganisation of a layer is triggered by violating application-specific constraints. HiSPADA is also able to work with predefined hierarchies which may e.g., be given as a utility's organisational structure. It then creates sub-hierarchies, appending to the given, fixed hierarchy.
An illustration of a sample hierarchy and the mapping to the system structure levels is given in Figure 2.1.

In conclusion, two adaptation mechanisms to form system structures and adapt to changes at different system levels can be stated in the APM:

[3]Instead of SPADA, HiSPADA is also able to utilise other partitioning algorithms, fulfilling certain requirements described in (Steghöfer et al. 2013).

[4]based on (Steghöfer et al. n.d., Fig. 2)

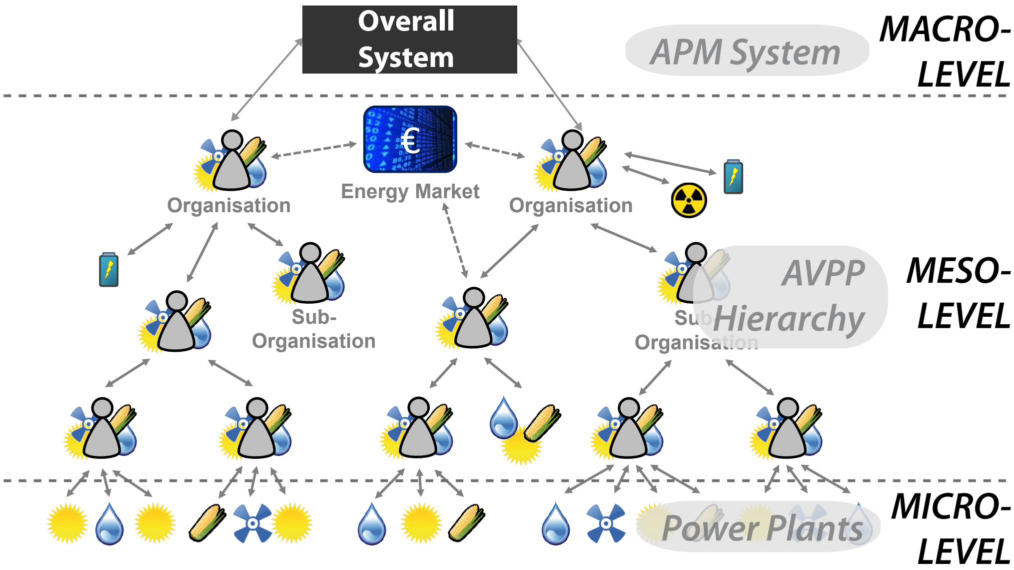



**Figure 2.1:** Structure levels of the APM System of Systems. Power plants are autonomously combined in AVPPs which themselves are nested within AVPPs forming a hierarchy.[4]

a) **an intra-organisational self-evaluating, introspective adaptation mechanism**
As described in Section 2.1, the scheduling algorithm solves the CSOP of load balancing within an AVPP (i.e., within an organisation). It is self-evaluating as it evaluates whether it is fit for purpose, based on both the CSOP feasibility and criteria like energy and trustworthiness mix, which it evaluates through introspection (i.e., self-examination through e.g., survey).
However, if an AVPP is part of a hierarchy and contains nested AVPP, it is important to consistently stipulate the organisation boundaries. In this case, nested AVPPs and thus nested organisations are not considered as separate organisations, so the notion of scheduling being intra-organisational holds for all AVPPs, independent of their substructure.

b) **an inter-organisational self-organisation meso-level structuration mechanism**
HiSPADA creates and adapts AVPP hierarchies by its control loop which monitors and affects layers of AVPPs (i.e., several organisations) in a self-organised fashion. Since the AVPP hierarchy reflects the system's meso-level, as illustrated in Figure 2.1, HiSPADA constitutes the APM's meso-level structuration mechanism.

### 2.3.2 Interference of Self-Organising Adaptation Mechanisms in Systems Of Systems

As the APM's introspective AVPP-dissolution mechanism, which is based on the scheduling process, affects the APM meso-level structure, as well as does the meso-level structuration mechanism, implemented by HiSPADA, there are two independent mechanisms working on the same structural elements which inevitably results in mutual influences and interferences. Thus, one main goal of this work is the investigation of interference patterns emerging by the interleaving of adaptation mechanisms at different levels within a SoS, which are given as a self-organising meso-level structuration- and an introspective self-evaluating-algorithm. The investigation, including the following scopes is described in Chapter 5:

- **Nested AVPP hierarchy implications**
  As AVPPs that are part of a non-flat hierarchy necessarily contain other AVPPs, that may themselves contain nested AVPPs and so on, are, and if, how are the dissolution criteria values propagated through the hierarchy and what resulting effects can be observed?

- **Meso-level structure endurance and structure-pattern oscillation**
  Since AVPP reformations and hierarchy-layer changes can be considered as structural short-time disturbances, will these changes promote the long-time endurance of the organisations? Through the existence of feedback loops in the APM's adaptation mechanisms, can emerging oscillations in structure changes be identified?

- **Interleaving effects at the macro-level**
  Which patterns of interference of the micro- and meso-level adaptation mechanisms along with the respective influence on the system behaviour can be identified and how can the emergence be controlled in order to optimise the achievement of macro-level goals (e.g., stability)?

## 2.4 Related Work

### 2.4.1 Virtual Power Plants

The notion of Virtual Power Plant (VPP) has been introduced in the late nineties as a combination of locally dispersed power producers, and has been widely adopted by both science and industry visions since the number of Distributed Energy Resources (DERs), such as photovoltaic power plants or wind turbines, started to grow significantly at the beginning of the new millennium,

undergoing various conceptual changes and variations. Reduced to a common denominator, a VPP constitutes a set of logically and physically interconnected DERs, where their power productions are aggregated and represented by a single entity acting like a conventional power plant, the VPP, which in most definitions is under central control. (Santjer et al. 2002, Dielmann & van der Velden 2003)
To express the high variability of the VPP notion in literature, the following categorisation criteria can be identified. For brevity, literature references are abbreviated using the mapping, defined in Table 2.1.

**Scope**
few DERs/VPPs (e.g., in ¤, ∘), *smart-* (e.g., in ✠, ■) and *micro-grids*[5] (e.g., in ‡, †)

**Control approach**
mostly centralised, rarely decentralised (e.g., †, ■)

**Element limitation**
some approaches limit possible VPP constituents to certain producer or consumer types (e.g., electrical car and wind mills only)

**Element type combination**
arbitrary subset of producers, consumers and storage (storage is either modelled as consumer or as explicit type) (e.g., regarding devices, DERs, consumers and different controllers in the MAS approach †; power producers and power storage, e.g., in ♡; producers (stochastic and dispatchable generators) and controllable load, in ∘; producers and consumers, e.g., in ♣; producers only, e.g., in ¤, ♠, ✠)

**Structure**
static only, despite AVPP approach (dynamic through self-organisation) and decentralised optimisation in ♠

**Differentiation of VPP types**
some approaches distinguish between commercial and technical VPPs and design interfaces regarding their system participation which is the power market and the power grid infrastructure respectively (e.g., ¤)

The different approaches involving VPPs cover various goals alike. The enhancement of the visibility of a group of DERs (i.e., a VPP) *(A)* is a central

[5] 'A smart grid integrates advanced sensing technologies, control methods and integrated communications into current electricity grid – both at transmission and distribution levels. [...] A microgrid is defined as an integrated energy system consisting of interconnected loads and distributed energy resources which as integrated system can operate in parallel with the grid or in an intentional island mode.' (Pipattanasomporn et al. 2009, p. 1).

**Table 2.1:** Mapping from identified goals to approaches in literature and their respective domain. Following abbreviations are used to refer to publications: ¤:(Pudjianto et al. 2007), ∘:(Mashhour & Moghaddas-Tafreshi 2009), ⊗:(Dielmann & van der Velden 2003), ⊙:(Santjer et al. 2002), •:(Lombardi et al. 2009), ‡:(Rahman et al. 2007), ✠:(Pipattanasomporn et al. 2009), †:(Ghosn et al. 2010), ■:(Awad & German 2012), ♣:(Wedde et al. 2006), ♢:(Wedde et al. 2008), ♡:(Peikherfeh et al. 2010), ♠:(Yang et al. 2013)

| **↓Goal / Domain→** | Power Systems | MAS | OC | Optimisation |
|---|---|---|---|---|
| A) Visibility | ¤ ∘ ⊗ ⊙ | ‡ ✠ | ■ | |
| B) Controllability | ¤ ∘ ⊗ ⊙ • | ‡ ✠ † | ■ | ♠ ♣ ♢ |
| C) Market access | ¤ ∘ ⊗ | ‡ | | ♠ |
| D) Self-*: failures, power surplus/shortages | | † ✠ | ■ | ♡ ♣ ♢ |
| E) SO Power routing | • | ‡ | ■ | |

goal, motivated by the nature of DERs, which are to replace power production from conventional power plants, but in the case of small installations feeding in the low-voltage band, are invisible to the grid operators, as their power contribution is perceived as diminished load only. So their capacity-displacement is not recognised by the operators, which results in over capacity, underutilisation of assets and ultimately decreased overall power production efficiency, according to Pudjianto et al. (¤). Being of similar importance, a large number of approaches also include the goal of enabling control over DERs *(B)* i.e., control of controllable power plants or consumers, in a mostly centralised and rarely decentralised manner. Again, the main contribution origins from ¤. To maximise both collective and individual profit, VPPs are to enable market access for groups of DERs *(C)*. Beside wholesale market access (e.g., in ¤, ♡, ∘), some approaches (additionally) introduce self-organised intra-VPP markets to deal with power over-production or shortages within a VPP (e.g., in ♣, ∘). The demand-supply-imbalance issue is also tackled on a small scale by approaches utilising self-configuration and self-healing techniques *(D)*, which operate on elements of the power distribution system infrastructure (like circuit breakers, voltage regulators, voltage regulators, etc.) and also allow for self-organised power routing (e.g., in ■). From the optimisation domain, market-based high-frequency price negation is proposed in ♣ to both maximise profit and compensate production-demand deviations.
Table 2.1 gives a mapping from the identified goals to approaches in literature and their respective domain. Please note that it is of limited representativity, as a) the focus on this related work research is on the general VPP concept and

contributions from mainly the Organic Computing and MAS domain, b) the listed goals and domains are not exhaustive, as well as c) the domain-approach mapping is not disjoint. Approaches are mapped according to their main goals and contributions to give a rough overview of VPP related work in literate.

Despite the high variation of VPP concepts, the approaches suffer from drawbacks. Originated by the nature of the most contributing domain, the power systems domain, it can be concluded that the VPP concepts are rather narrow through their technical scope and their focus, which is mainly on the technical feasibility rather than on software system concepts, resulting in an overall limitation of the potential of the proposed VPP concepts. Furthermore, the scope of the proposed VPPs, in approaches not including MAS and Organic Computing (OC), and the regarded power network is still on an abstract level, which lays orders of magnitudes under realistic scales. As a last drawback, individual publications only include one or very few approaches, lacking a holistic point of view, which may be due to, or at least supported by, the high number of conceptual variations and the partly tough restrictions, as described above.

### 2.4.2 Interferences in Autonomic Manager Interoperability

In the domain of Autonomic Computing (AC), Autonomic Managers (AMs) proactively monitor the state of a System under Observation and Control (SuOC), analyse it in order to identify deviations from given target-states, determined by a knowledge base or by high-level goals, and in case of such deviations, plan and execute an action or action sequence in order to return the SuOC to a desired state. In presence of multiple AMs, conflicts may arise by either AMs managing a same resource with conflicting goals or AMs managing different resources which however have an undesirable impact on the management function of other AMs.

A classic example for conflicting goals and negative interaction of AMs is the case of a performance manager, striving to decrease task execution time by increasing a computer's computing power in case of high load (thus increasing its power consumption) and a power manager, striving to minimise a computer's power consumption. Several papers deal with this specific problem, such as (Rong & Pedram 2005, Khargharia et al. 2006).

The interoperability of AMs depicts a coexistence of adaptation mechanisms (i.e, the AMs) and thus potential interference of themselves. However, the interference pattern in the aforementioned case is not only rather trivial and static but also known at design time.

In the general case, interference patterns may be much more sophisticated by e.g., emerging oscillations through feedback loops, and may not be foreseen easily. Anthony et al., Eze et al. tackle potential general AM interoperability issues by introducing an addition control loop, consisting of an ad-hoc correctness validator which, if failing, gives immediate *control feedback* to the AM, and an element performing long-term behaviour tracking and impact-/effect-analysis as well as corrective intervention through *recalibration feedback* to the AM, if necessary, combined as *interoperability service*.

However, the difference to the investigation in this work is that the research topic and the goal of the mentioned contributions from the AC domain is, in a nutshell, a methodology for detection and reconciliation of conflictious AM-interactions rather than investigation of interference patterns.
Also, the mentioned general approaches do not consider hierarchical interactions on different levels of a SoS. There are approaches that address AM-hierarchies e.g., (Rong & Pedram 2005, Khargharia et al. 2006), but these are limited to the dedicated problem of interoperability of performance- and power managers, as mentioned.
In conclusion, it can be stated that though the AC domain faces similar topics in the AM-interoperability, its contributions are not closely related to the investigation of this work.

# Chapter 3

# Enduring Electronic Institutions

In open, embedded and resource-constrained systems with decentralised control, competition for resources and expectation of both intentional and unintentional errors, like an AVPP, Pitt et al. (2011) state that the 'optimal' distribution of resources is less important than the 'robustness' or 'survivability', hence the endurance, of the distribution mechanism. In the first part of this chapter, a general overview over resource allocation mechanisms and the implication with respect to endurance of the organisation is given. Pitt et al. model a collective-decision making based distribution mechanism system and adopt socio-economic principles for building enduring and fair institutions. These principles consist firstly of principles for enduring self-governing institutions, as concluded by Elinor Ostrom (Section 3.3), and secondly on design principles for allocation systems incorporating distributive justice, based on the work of Nicolas Rescher (Section 3.4), and are briefly presented in the second part of this chapter. Pitt, Schaumeier, Busquets & Macbeth (2012) complement two of Ostrom's principles with an allocation method based on canons of distributed justice, which is described in Section 3.5.

## 3.1 Common-pool resource allocation and the Tragedy of the Commons

In a Common-Pool Resource (CPR) allocation system, the divisible pooled resource is public but restricted in quantity, while the system components 'are required to share and appropriate resources in order to satisfy individual goals'. The resources may either be exclusively exogenous (provided by an external source) or endogenous (system-components-provided) or a mixture of both.
Game theory predicts an unsuitable CPR allocation system leading to the *Tragedy of the Commons* which describes the dilemma of rational agents, that are dependent on a limited CPR, acting independently and rationally according

to each one's self-interest in allocating such an amount of resources, that the common pool is depleted in the short-term, although this behaviour is in contrast to both the group's and the individual agents' long-term interest (Hardin & U.S.-Environmental-Fund 1982). The depletion of the resource renders depending individuals or organisations unable to operate further. In economics this phenomena can be found in a large number of systems, tightly connected to the concept of endurance and sustainable development, like fishery, water irrigation, farming, with respective *commons* fish, water and soil or meadows. (Ostrom 1990)

As a simple example, Hardin & U.S.-Environmental-Fund (1982) provides the situation of a rational herder, who receives a direct benefit from putting his animals on a publicly accessible pasture to graze. As other herders also use the common-pool resource 'grass', each herder also suffers delayed costs from the deterioration of the resource which raises a race-condition, where each rational herder is incentivised to put more animals to graze, earning more profit, while only suffering a share of the costs of overgrazing he additionally causes. This individual rational behaviour ultimately leads to a situation where the collective resource gets depleted, which is in complete contrary to the individuals' interest.

## 3.2 The Linear Public Goods Game: An exemplary resource allocation system

The Linear Public Goods Game (LPG) is a classical experiment in game theory and serves as a simple example of an allocation system of endogenous CPR. In the LPG, as illustrated in Figure 3.1, a set of $n$ players, $P$, are each endowed with 'tokens', i.e., resources, of quantity $z$ by the game and thus exogenously. Each player $i$ then has to choose an amount of tokens $g_i$ to contribute to a common pool. Therefore, the LPG is also called *voluntary contribution game*. The endogenous provisions are then summed up and multiplied by factor $\alpha > 1$. The CPR is then distributed equally among all $n$ players. After getting this allocation from the LPG allocation scheme, each player $i$ appropriates the allocated amount of resources and gains a utility based on its individual payoff $\pi_i$ which is given as:

$$\pi_i \;=\; z - g_i \;+\; \frac{\alpha}{n}\sum_{j\in P} g_j \;, \text{ where } \alpha > 1,\ \frac{\alpha}{n} < 1 \tag{3.1}$$

The first term of the payoff depicts the amount of resources not spent to the common pool and is thus called private payoff $p_{private} = z - g_i$, whereas the uniform share of the common pool is called public payoff $p_{public}$. Because $p_{public}$ does not depend on the individual provision, there is a strong incentive not

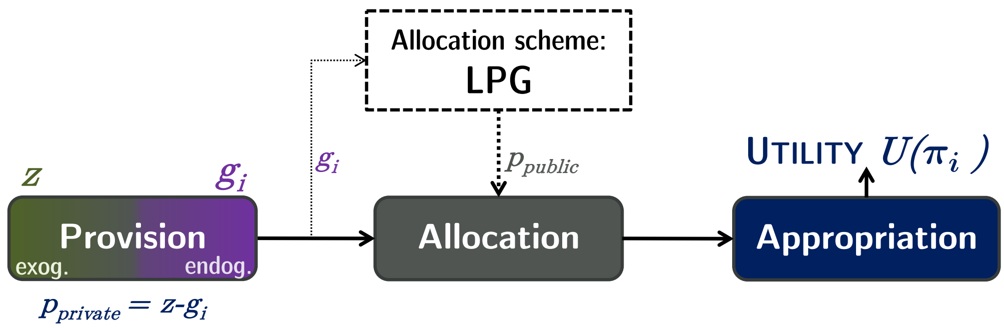



**Figure 3.1:** The LPG allocation system: players may contribute their resources to a public pot (provision) which is multiplied and equally distributed to all players (allocation) regardless of their contribution at the end of a round. Each player assesses a total utility for both not contributed and allocated resources (appropriation). Depending on the pot multiplication factor the players are incentivised not to contribute resources at all.

to provision at all while profiting from the contributions of others, i.e., to free-ride. As each provisioned token by a player gets multiplied, but returns only as a fraction $^{\alpha}/_{n} < 1$ to the provisioning (and all other) player, whereas not provisioned tokens are kept in full quantity (1) there is a Nash-equilibrium at $g_i = 0$.
The tragedy herein lays in the fact, that $p_{public}$ increases with every provision and reaches its maximum $z\alpha$ when all players fully contribute their tokens ($g_i = z$, $\forall i \in P$), but the dominant strategy is to withheld all tokens, leaving the players with only $z$ tokens each when $g_i = 0$, $\forall i \in P$, which clearly is of lower utility for intuitive monotonous utility functions. (Gächter 2006) (Pitt, Schaumeier & Artikis 2012)

## 3.3 Ostrom's Principles for Enduring Organisations

Ostrom (1990) observed, through intensive field studies on human societies, that CPR management does not necessarily need to result in a *Tragedy of the Commons*, as game theory would predict. To circumvent the tragedy, she spotted an alternative to centralised control of the resource or privatisation, in delegating the government of commons to *institutions*, as many communities in the US, Switzerland and Japan do according to her observations. Her notion of institution describes a set of working rules, regulating and constraining provision to and appropriation from the resource, rather than an organisational

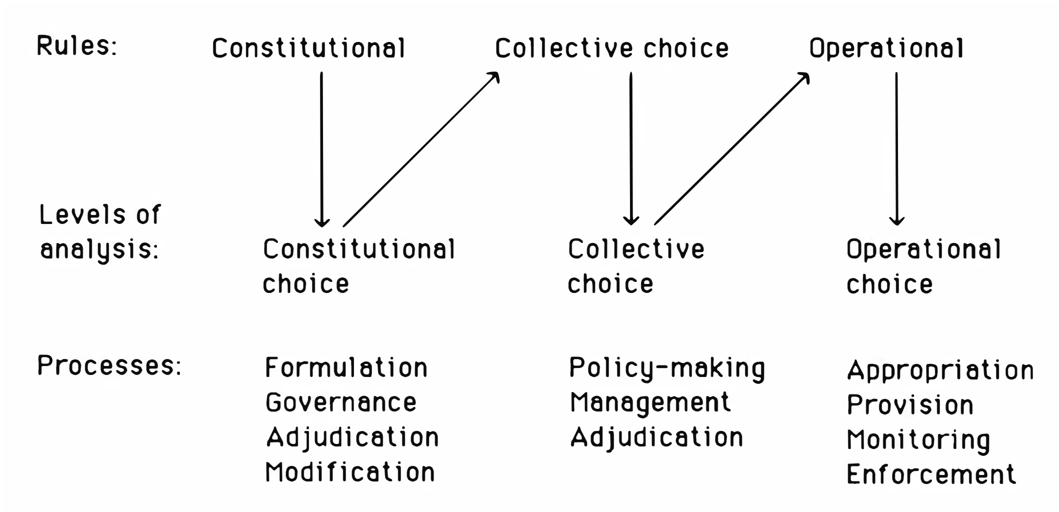



**Figure 3.2:** Ostrom's three levels of rules: operational, collective choice and constitutional (Ostrom 1990, Fig. 2.3).

structure. These rules are used 'to determine who is eligible to make decisions in some *arena*, what actions are allowed or constrained, what aggregation rules will be used, what procedures must be followed, what information must or must not be provided, and what payoffs will be assigned to individuals dependent on their actions' (Ostrom 1990, p. 51). The working rules are always monitored and enforced and known by every participant.
By the concept of an arena, Ostrom denotes 'the situation in which a particular type of actions occurs' (Ostrom 1990, p. 54), with respect to the scope of the rules who are effected by these actions, which is distinguished in three levels, as shown in Figure 3.2: (1) Operational choice rules, defining restrictions on the appropriation and provision of resources, the monitoring as well as rule-enforcement, (2) Collective-choice rules defining the operational rules, i.e. how a CPR should be managed and (3) Constitutional-choice rules, defining which specific rules are to be used to craft the set of collective-choice rules and who is eligible to participate in this process (Ostrom 1990, p. 52).
Ostrom identified eight design principles for self-governing CPR management institutions to endure, which are listed in Table 3.1.

## 3.4 Rescher's Legitimate Claims and Canons of Distributive Justice

Raising the question about design principles of fair allocation mechanisms, especially concerning the fairness of the outcome for the participants, analyses in the field of *distributive justice* offer paradigms of rich conceptual expressiveness

**Table 3.1:** Ostrom's Priciples for Enduring Institutions.
(Pitt, Schaumeier & Artikis 2012) (Ostrom 1990, p. 90)

| | |
|---|---|
| **P1** | **Clearly defined boundaries**<br>Those who have rights or entitlement to appropriate resources from the CPR are clearly defines, as are its boundaries. |
| **P2** | **Congruence between appropriation and provision rules and local conditions** |
| **P3** | **Collective-choice arrangements**<br>In particular, those affected by the operational rules participate in the selection and modification of those rules. |
| **P4** | **Monitoring**<br>Monitors, who actively audit CPR conditions and appropriator behaviour, are accountable to the appropriators or are the appropriators. |
| **P5** | **Graduated Sanctions**<br>A flexible scale of graduated sanctions for resource appropriators who violate communal rules. |
| **P6** | **Conflict-resolution mechanisms**<br>Access to fast, cheap conflict-resolution mechanisms. |
| **P7** | **Minimal recognition of rights to organize**<br>Existence of and control over their own institutions is not challenged by external authorities. |
| **P8** | **Nested enterprises** (for CPRs that are part of larger systems)<br>SoS: layered or encapsulated CPRs, with local CPRs at the base level. |

to be adopted. In his studies about distributive justice, Rescher assesses fairness based on the principle of utility. According to the doctrine of classical utilitarism, any fair distribution should follow the utility-rule 'the greatest good of the greatest number' which he concludes to be imprecise and inadequate (Rescher 1967, p. 8f).

Based on comprehensive related works he states that justice since has been held to consist to treat all people wholly or primarily according to one of seven principles to be used as ultimate determinant of individual claims, e.g., as equal or according to their needs. He canonised these treatment principles as the seven canons of distributed justice, as shown in Table 3.2. However, Rescher concludes that justice does not hold by valuing the individual claims on basis of only one canon, as they are monoistic, each recognising but one solitary mode of claim production. Instead, he states, that distributive justice consists in the pluralistic *Canon of Claims* which treats people according to all their legitimate claims, positive and negative, i.e., according to a valuation of all canons (Rescher 1967, p. 81f). Since this canon formalisation origins in the context of a discussion about a just wage determination, Rescher states that not all canons may be adequate in other contexts, raising the need for an individualised canon selection within the Canon of Claims.

## 3.5 Fair Self-Organising CPR Allocation

To cope with common characteristics of open systems, such as agent autonomy, especially regarding deliberate leaving and joining a system and acting selfishly, e.g., through not complying to rules, as well as decentralised decision-making, also regarding resource allocation, Pitt, Schaumeier, Busquets & Macbeth (2012) introduce a variant of the LPG, the Varied Linear Public Goods Game (LPG'), to cover a typical resource allocation scenario in open systems. As a further complication the LPG' assumes an economy of scarcity, meaning that the total amount of required resources exceeds the amount available resources. Pitt et al. unify Ostrom's principles with Rescher's canons of distributive justice to establish a resource allocation system for open systems ensuring fairness and endurance, gaining a better balance of utility and fairness, for compliant agents, and hence improved stability.

The LPG' is repeatedly played in clusters of agents, where a game step consists of the following action sequence, also illustrated in Figure 3.3: (I) Determine the resources available (keep it secret), (II) determine the need for resources (keep it secret), (III) make a demand for resources (publish its public demand), (IV) make a provision of resources (to the public pool), (V) receive an allocation of resources from the system and finally (VI) make an appropriation of resources (actual appropriation from the pool), which may be higher than the allocation.

**Table 3.2:** Rescher's Canons of Distributed Justice (Rescher 1967, pp. 73-80)

**C1 The Canon of Equality**
Treatment as equals (except possibly in the case of certain "negative" distributions such as punishments).

**C2 The Canon of Need**
Treatment according to their needs.

**C3 The Canon of Ability**
Treatment according to their ability or merit or achievements.

**C4 The Canon of Effort**
Treatment according to their efforts and sacrifices.

**C5 The Canon of Productivity**
Treatment according to their actual productive contribution.

**C6 The Canon of Social Utility**
Treatment according to the requirements of the common good, or the public interest, or the welfare of mankind, or the greater good of a greater number.

**C7 The Canon of Supply and Demand**
Treatment according to a valuation of their socially useful services in terms of their scarcity in the essentially economic terms of supply and demand.

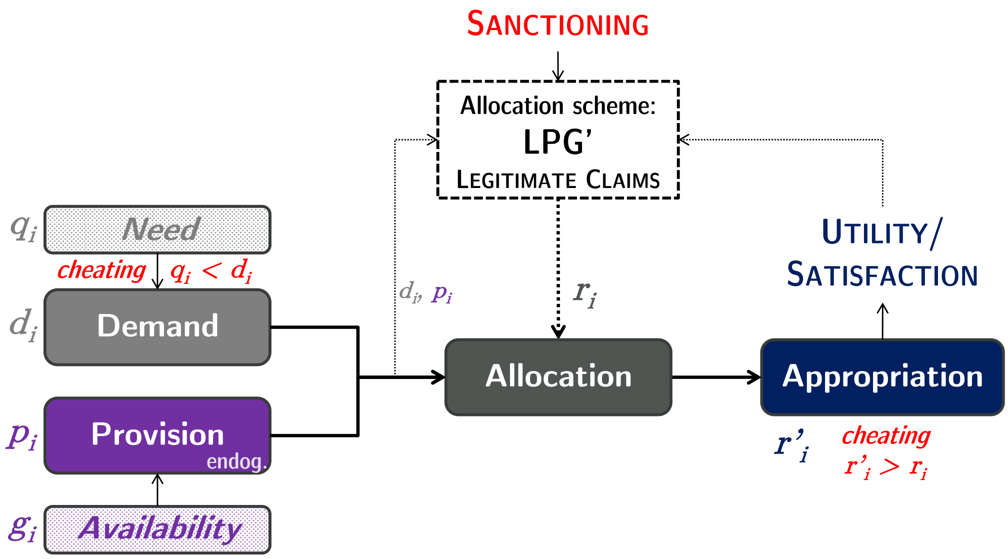



**Figure 3.3:** The LPG' allocation system based on legitimate claims: each player publishes its resource demand and provisions resources. According to the individual legitimate claims valuation, each player gets an individual allocation and appropriates resources, which may be of higher quantity than the actual allocation in the case of non-compliant behaviour. The assessed satisfaction is fed back to the allocation scheme in form of a claim, as is potential non-compliant behaviour, thus incorporating a simple sanction mechanism.

As the need for resources of an agent $i$, is greater than its supply ($q_i > g_i$), agents are dependent on the contribution of other agents. This scarcity also raises incentives, firstly not to contribute at all, like in the LPG, and secondly to violate rules in order to increase the amount of appropriated resources. Beneficial rule violation, i.e., **cheating**, of an agent $i$ is possible in two places in the system: (1) publishing a higher demand than internally determined ($d_i > q_i$), knowing that the demand is considered in the allocation, and (2) appropriate more than got allocated ($r'_i > r_i$). Because an agent's internally determined need is kept private, violations of type 1 cannot be monitored, unless the agents are forced to reveal their internal state in this respect. However, **sanctioning** of violations of type 2 is enforced through monitoring of $r'_i$ and $r_i$ and respective reporting and feeding back non-compliant agent behaviour to the allocation scheme, which considers and punishes the misbehaviour in the next rounds, by reducing the allocated resources of a non-compliant agent. Thus, compliance to rules is incentivised.

A major extension to the LPG is the introduction of satisfaction which each agent assesses by the deviation of its allocation and its need in each game round. Satisfaction or dissatisfaction accumulates through reinforcement over the game rounds and leads to abandonment of the cluster when the satisfaction falls below a certain threshold. An abandoned cluster will never be joined again by the agent.

Given this notion of satisfaction, it is obvious that the actual **allocation scheme**, also called ration policy, plays a crucial role for an agent's satisfaction. The most trivial ration policy is a uniform distribution of the public pool to the agents. Pitt & Schaumeier (2012) proposed the *Ration+* policy, where the resource excess, from agents whose allocation is greater than their demand, is redistributed to the agents whose need is greater, leading to an overall increased satisfaction. Because, as mentioned before, Pitt, Schaumeier, Busquets & Macbeth (2012) showed that when a distribution method is deemed fair by the participating agents in a CPR allocation scenario, the overall utility and satisfaction is increased, Rescher's canons of distributive justice are used in the LPG' in form of legitimate claims.
An agent's legitimate claims are determined by a valuation of its relative merits, each based on one canon. Therefore functions, each representing one claim, calculate ranking lists which order the agents based on their merits regarding that particular canon. The set of functions ($F$) in the LPG' is defined as follows (Pitt, Schaumeier, Busquets & Macbeth 2012, p. 3f):

- $f_1$: **The canon of equality**
  Firstly rank the agents in increasing order of their average allocations,

secondly in increasing order of their satisfaction, thirdly in increasing order of the number of rounds in which they received an allocation.

- $f_2$: **The canon of needs**
  Rank the agents in increasing order of their average demand.
- $f_3$: **The canon of productivity**
  Rank the agents in decreasing order of their average provision.
- $f_4$: **The canon of effort**
  Rank the agents in decreasing order of the number of rounds spent in an ordinary role.
- $f_5$: **The canon of social utility**
  Rank the agents in decreasing order of the number of rounds spent in an elevated role.
- $f_6$: **The canon of supply and demand**
  Rank the agents in decreasing order of compliance to the norms.
- **The canon of merits and achievements** is meaningless in the LPG' context and thus unrepresented.

Supplementary to the semantic explanations of the claims in Table 3.2, important notes about the claims in the context of the LPG' are given below: The canon of equality proactively equalises the agents by compensating differences in the given equality factors, i.e., average allocations, satisfaction and number of allocations, through prioritisation in the valuation of the agents in an increasing order, according to increasing different values of these factors between the agents. Note that every agent individually assesses its satisfaction as a reinforced demand-allocation-deviation measure based on its allocation from the last rounds which is the output of the claims. As the satisfaction is also the input to the allocation scheme, in form of a claim, there exists a feedback loop. Assuming, that demands average-out over time, as the agents in the LPG' are considered to be homogeneous, the canon of needs orders the agents in *increasing* order of their average demand, because the most deserving agents are those who made the least demands. This also incentivises a truthful report of demands.

Note also that rule violations through over-appropriation (type 2) as discussed earlier, are sanctioned through the canon of supply and demand which ranks the agents proportional to their degree of compliance. This sanctioning mechanism is sufficient to 'enforce' compliance in this regard – a more explicit sanctioning mechanism is not needed.

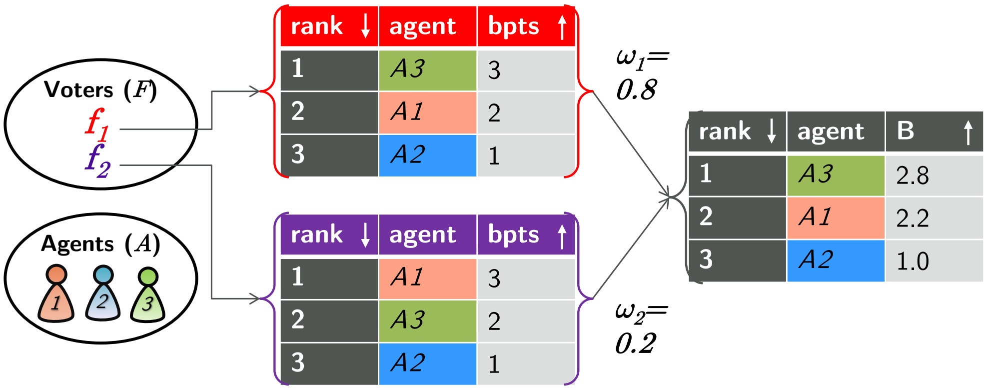



**Figure 3.4:** A minimalistic example of the Borda count voting protocol, as utilised in the LPG': Agents are ranked through a set of voters, each creating an individual rank list. Borda points are associated with each rank in a list and aggregated through a weighted sum, resulting in a single final rank list and final associated Borda score for each player.

To implement the canon of claims, i.e., to combine the individual claims listed above, the *Borda count voting protocol* is used, wherein each canon represents a preferential voter $f_* \in F$. As illustrated in a minimal example in Figure 3.4 and explained in more detail in (Pitt, Schaumeier, Busquets & Macbeth 2012), each voter creates a rank list, by computing the rank of each agent. The rank computation of a voter $f_*$ for an agent $i \in A$ shall be done by the function $f_*(i)$. Every rank list assigns Borda points to an agent with rank $r$ as follows:

$$bpts(r) = n - k + 1, \text{ where } n = |A| \tag{3.2}$$

The Borda points of an agent from each ranking list are aggregated to a resulting total Borda score. In order to reconcile conflicts between the claims, Pitt, Schaumeier, Busquets & Macbeth (2012) utilize a weighted sum as aggregation function, attaching a weight $\omega_* \in [0,1]$ to each claim $f_* \in F$. The final Borda score $B(i, F)$ of an agent $i$ is given as follows:

$$B(i, F) \;=\; \sum_{*=1}^{|F|} \omega_* \cdot bpts(f_*(i)) \tag{3.3}$$

A Borda count queue in decreasing order of the total Borda score is then built and resources are allocated to the agents in decreasing order of the Borda queue (i.e, following the first-in first-out principle) and in full quantity of their demands, until the resource pool is depleted.

The weights, attached to each canon, are determined by the agents themselves in a self-organisation process, based on collective-choice-rules of an self-organising electronic institution which Pitt et al. model for the LPG'. They are updated at the end of a round. Three functions influence the canon weights for the next round which are very briefly described as follows: (1) self interest: the agents promote those canons who gave them each the highest rank, (2) countering self-interest and avoiding path-dependency: canons whose rank order was close[1] to the final rank order, i.e., the combination of all canons, get their weights decreased and vice-versa, and (3) institutional homeostasis: restoring an equilibrium state, where all weights are equal. A more precise explanation can be found in (Pitt, Schaumeier, Busquets & Macbeth 2012, p. 6f).

Although Pitt et al. primarily address Ostrom's second and third principle (P2: congruence between appropriation and provision rules and the state of the prevailing local environment; P3: collective-choice arrangements) the LPG' implements other Ostrom principles (see Table 3.1):
In the formal electronic institution definition, the roles declare cluster membership. As only agents that are members of a cluster get resource allocations, and those are clearly distinguishable, P1 is fulfilled. Appropriation and provision rules are defined in the electronic institution as well as through the allocation scheme, which both take into consideration, the economy of scarcity and the state of the local environment, i.e., the total amount of provisions and demands, thus fulfilling P2. P3 is adopted in the self-organising claim-weight determination, which is based on a voting mechanism, where all agents that are affected by this mechanism are involved in the collective-choice arrangement process through votes. Also, P5, demanding graduated sanctions are implicitly adopted through the feedback of detected non-compliance to the allocation scheme.

[1]measured by the hamming distance metric

# Chapter 4

# Model Synthesis: Self-organising legitimate claim resource allocation for APM scheduling

This chapter firstly declares the motivation to utilise a self-organising legitimate claims based CPR allocation system to formalise the APM scheduling within an AVPP, and stipulates requirements a solution approach should suffice. This especially includes the incorporation of Ostrom's principles for enduring institutions and Rescher's canons of distributive justice, which demand promoted agent-autonomy, possibly contrasting the nature of mission-critical systems. The starting point for the implementation of the stipulated requirements is the modification of the LPG', as defined in (Pitt, Schaumeier, Busquets & Macbeth 2012) and described in Section 3.5, followed by the adoption of this modified LPG' to the APM through the reformulation of the scheduling process and completed by the implementation of the introspective satisfaction-based AVPP dissolution mechanism. Accordingly, first the global view on the approach is given in Section 4.2, introducing basic concepts and stating the involved institutions, their relations and interactions. The implicit mapping of the APM to LPG' paradigms in the overview is explicitly explained and refined in the following Section 4.3, where significant conceptual differences and their implications for the solution approach are identified. Details of the implementation are given in the subsequent Section 4.4, starting with an overview of the APM allocation system and the introduction of basic notions, followed by an explanation of the demand determination and deviation- and satisfaction metrics definition. After the resource case-dependent allocator sequence derivation is presented, the APM allocation system's main allocator based on legitimate claims is explained, including a description of the APM-specific claims. Lastly, the modified AVPP dissolution mechanism is presented in Section 4.5.

## 4.1 Motivation and Requirements for formulating the APM scheduling as self-organising CPR allocation

The APM, as an exemplary system in the energy and power domain, incorporates institutions on two different levels of abstraction, which is the macro–level power grid system itself, as well as the AVPPs as intermediary institutions, encapsulating CPPs or other AVPPs. The endurance and stability of the power grid system is easily identified as a main goal of utmost importance. Fluctuations in the APM's meso-level structure, the AVPP-hierarchy, constituted by the AVPPs, due to sub-optimality and low average fitness/utility poses a threat to the macro-level system stability and is thus to be minimised as are other potential distortions of the macro-level system. As described in the chapter before, Ostrom identified eight principles as necessary and sufficient conditions for an institution to endure. As endurance on multiple levels of abstraction is a necessity for systems to endure, like the APM, one a major goal of this work is the adoption of Ostrom's principles in the allocation mechanism of a Power Management System (PMS) at hand, the APM. Since the APM's allocation mechanism is incorporated in the scheduling process, the same is reformulated to satisfy the requirements, which are stipulated within this section, in terms of endurance and fairness, beginning with stipulating **requirement R1**: the adoption of Ostrom's principles to the APM's scheduling. Because the PPPs are physical components, physical restrictions, such as maximum power production and slope, are to be treated as hard constraints and are not to be violated by the scheduling, as **requirement R2** shall demand.
Ostrom's third principle demands collective choice arrangement, meaning that those who are affected by rules and thus have stake, should participate in the selection and design of those rules. In partial fulfilment of R1, this is realised by complementing the APM's top-down AVPP-dissolution mechanism by a bottom-up approach where power plants form a collective opinion whether to trigger the dissolution of their AVPP based on their individual fairness assessment about the outcome of the modified scheduling, i.e., the load allocations. This approach is also perfectly congruent with the MAS inherent agent autonomy and demand for a high level of self-organisation.

As showed by Pitt, Schaumeier, Busquets & Macbeth (2012), a system's overall agent utility gets increased when the agents deem to be treated fairly. As legitimate claim resource allocation promotes overall fairness and agent satisfaction over time, the application of Rescher's canons of distributive justice in the APM's scheduling process are highly motivated as it would diminish the APM's meso-level fluctuations and thus formulate **requirement R3**: establish and promote fair agent treatment in the scheduling, i.e., maximise agent satisfaction therein. To live up to the technical nature of the APM and its embeddedness in an economic system, i.e., the power market, the fairness assessment of the power plants should incorporate also economic factors, reflecting the economic power plant model data, like (economic) optimal power production and distinctive implications of deviations from this optimum, both positive and negative, which shall be subsumed by **requirement R3'**.

## 4.2 Approach Overview: Concepts, Organisations & Interaction Interfaces

Figure 4.1 gives a high-level overview of the target system. There are three kinds of 'organisations' involved: first of all, the **AVPP** which is constituted of either PPPs or other, nested, AVPPs which stipulate the second type of organisations: the constituents, or children, of an AVPP. For brevity, in the following sections, speaking of an CPP in the role of a child of an AVPP includes also AVPPs being in the role as a child, without explicit notice. Since SPPs are not participating in the scheduling, they are omitted here, focussing on **CPPs** as being exclusively relevant. An AVPP gets load assigned from its father AVPP (not modelled here) and distributes this load to its children in the scheduling process, which delegates the allocation process to an **electronic institution**, the third and last organisation. Note that the partial fulfilment of R1, the adoption of Ostrom's principles, can already be stated at this point. Due to the inherent coupling of an AVPP and its constituents, in both structural and through the scheduling also in procedural sense, the borders of the organisation and the role of an appropriator are clearly defined, as demanded in P1. Also P8 is fulfilled, since AVPPs are nested in the APM which therefore is a SoS. The total demand to be satisfied in the whole APM system is delegated to encapsulated AVPPs on multiple levels, which are CPRs in this sense, which exactly meets P8.

Within the electronic institution, the **scheduling** is performed, based on a modified LPG' with APM-specific **canons** which partly determine the allocations for the constituents and fulfil R3 through the incorporation of fairness. These modifications and adaptations are explained in detail in the following sections of this chapter.

As described, a CPP gets a **load allocation**, i.e., a resource allocation, as the outcome of the scheduling of its AVPP, **appropriates** load and produces power, matching the appropriated load, which it **physically feeds** in to the power grid. There might be deviations from the allocated and appropriated

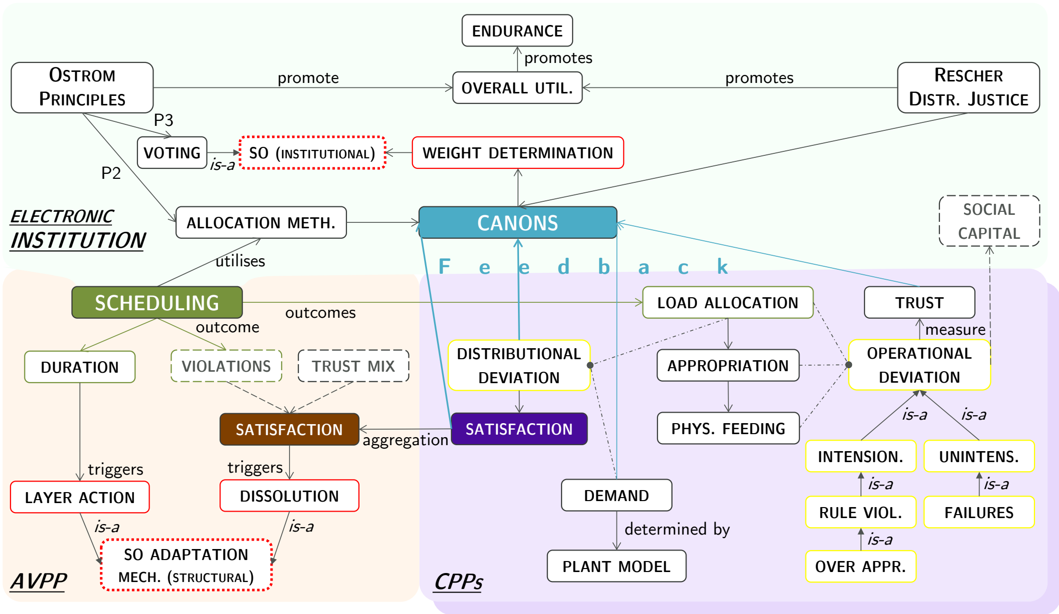



**Figure 4.1:** Semantic map of the final system, showing concepts, the involved organisations, their relations and interactions.

load and from the appropriated and produced, which are subsumed as **operational deviation**. Allocation-appropriation deviations are considered to be intentional, i.e. cheating, whereas deviations between appropriated load and actual production are considered to be unintentional, e.g., as a result of failures. Both kinds of operational deviations can be measured by a suitable **trust** metric and be fed back to the allocation system in form of a canon, sanctioning misbehaviour or unreliability. Additionally other power plants may step in to compensate malfunctioning plants, producing ***social capital***, as proposed for further work.
Based on its power plant model, a CPP determines and publishes a demand for resources to the allocation system. This process is explained in Section 4.4.1. However, dependent on the resource economy, it is likely to have a deviation between the quantity of demanded and allocated resources, expressed as **distributional deviation**. This deviation is quantified in different ways, as described in Section 4.4.1 to fulfil R3', since it is the basis for the **CPP satisfaction** metric, also defined in Section 4.4.1.

The satisfactions of an AVPP's constituents are aggregated and stipulate the **AVPP satisfaction**. It serves as a new and replaces the old criteria in the intra-organisational self-evaluating, introspective adaptation mechanism which may trigger the **dissolution** of that AVPP. Details about the satisfaction aggregation and the dissolution mechanism are elaborated in Section 4.5. An extension to be done in further work might be the implementation of a

multi-criteria satisfaction metric, complementing the CPP satisfaction aggregation with scheduling **violations**, the AVPP's **trust mix** or other user-defined criteria, to trigger the dissolution and thus the reformation of an AVPP.
The unaltered AVPP's inter-organisational self-organisation meso-level structuration mechanism is also active, triggering **hierarchy layer actions** in form of introducing new or removing existing layers, should the scheduling **duration** exceed given thresholds. Note that this describes the situation of two concurrently active **self-organising adaptation mechanisms**, affecting common structural elements, i.e., the AVPP and the AVPP-hierarchy, thus expectedly causing interference like introduced in Section 2.3.

In the global view on the target system, there is a total of three self-organisation mechanisms identifiable. Additionally to the above-mentioned self-organised structural adaptation mechanisms, the weight determination in the electronic institution of the LPG' (see Section 3.5) also stipulates a self-organisation process, but of organisational nature, incorporating voting and thus following Ostrom principle P3, which partially fulfils R1.
As denoted by ***feedback*** in Figure 4.1, a CPP's demand, distributional deviation, satisfaction and trust are published to the allocation system to be valuated as claims. Since the distributional deviation and thus also the satisfaction, also the trust in presence of operational deviations, are an indirect result of a load allocation, i.e. a scheduling outcome, and are used in claims to determine the allocation, i.e. the schedule, this represents a **feedback loop** in the system, which is to be considered as an additional source of interference, e.g. in the form of oscillations, in the interference investigation later on.

## 4.3 Conceptual Mapping: APM as Electronic Institution & Adoptability of the LPG'

In order to be able to adopt an electronic institution in form of the LPG' to perform the APM's scheduling process, first of all the congruence of the APM and the general specification of an self-organising electronic institution as described by Pitt et al. (2011) has to be analysed. Based on identified differences in their conceptual notions, the design principles of the LPG' have to be adapted to suit the requirements of the APM in the global system view as well as in the specificational view, considering the four requirements, defined in Section 4.1.
This comparative analysis, as summarisingly illustrated in Table 4.1, consists of four parts, reflecting conceptual domains which are subsequently described and named as follows: (1) the nature of the overall system and of players, (2) the role and manifestation of an institution, (3) allocation system rationales resource and demand and (4) the implementation of satisfaction.

**Table 4.1:** Concept mapping: Electronic Enduring Institutions and the APM

| Concept | Enduring institution (LPG') | APM |
|---|---|---|
| **System nature** | abstract | cyber-physical (real-world), mission-critical |
| **Player** | homogeneous abstract player | heterogeneous power plant |
| **Institution** | abstract "cluster" | macro-level: SoS (APM)<br>meso-level: AVPP |
| **Resource type** | abstract resource | power demand (load) |
| **Resource origin** | endogenous | exogenous |
| **Resource economy** | scarcity | scarcity/surplus each infeasible or feasible |
| **Resource allocation quantum** | full demand | arbitrarily |
| **Player demands** | arbitrarily, time-independent | static, time-dependent |
| **Satisfaction** | discrete | continuous |

The LPG' is built on the foundations of electronic institutions as a general approach, complementing Ostrom principles with the concept of distributional justice, on a theoretical and abstract scope, without immediate real-world application intention. Thus, its system nature is abstract, as are its players. There is neither individualisation nor differentiation in the player model — they are homogeneous. The institutional boundaries are defined through memberships to abstract clusters. In contrary, the APM as a PMS is a *Cyber-physical System (CPS)*, as its computational elements control physical entities (Lee 2006), and it is also mission-critical. The relevant actors, i.e., the players, in the APM are power plants, which are commonly classified by their energy source and exhibit distinctive characteristics thus. Furthermore, beside class characteristics, an individual power plant has individual properties, e.g., the maximum power output. Players in the APM are thus highly heterogeneous. The APM defines an institution itself on the macro-level, whereas an AVPP constitutes an institution in the meso-level.

The implication of the APM's cyber-physicality and mission-criticality is already partly covered by R2, which raises the need to handle the power plants physical restrictions as hard constraints. Since operational deviations obviously jeopardise the system goal 'stability of the power grid', it seems additionally legitimate to enforce compliance, i.e., forbid cheating, in the scheduling. This design choice renders sanctioning needless, sanctioning is already implicitly implemented by the legitimate claims though. The conflicting goals agent-autonomy and enforcing control, with inherent agent-autonomy diminishment, justified by the APM's mission-critical nature, are balanced though, since on the other hand, the LPG' based scheduling in the APM promotes agent-autonomy in several respects. The optimality of the former CSOP scheduling is sacrificed to both promoted agent-autonomy and degree of self-organisation as well as agent satisfaction and fairness.

Subsequently, the substantial difference in the level of abstraction in the systems is also reflected in the allocation system with respect to the type of resource, which is abstract in case of the LPG', whereas in the in the APM it is defined as the load, i.e., the power demand, the power plants are in competition to fulfil. To distinguish the ambiguous notions of 'demand', in the sense of demand for resources in a resource allocation system on the one and demand of electrical power in the PMS terminology on the other hand, the latter is referred to explicitly calling 'power demand' in the rest of this Thesis.
Also in the resource origin there is a major difference. It is provided by the participants themselves and thus endogenous in the LPG', but exogenous in the APM, as power producers do not provide load/power demand but, in contrary, their goal is to satisfy the load through their power production. The load is assigned from an instance outside the institution and thus is of exogenous nature.
The assumption of an economy of scarcity regarding the resources in the LPG' does not generally hold in the APM, where an economy of scarcity would mean that an AVPP's total optimum power production would exceed its assigned load, so that there would be a real competition between the AVPP's constituents to satisfy this load, i.e., to get the scarce resource load. Subsection 4.4.2 deals with the resource case determination in the APM which ranges from scarcity over variable to surplus, where the extremes may be exactly met in the feasible case, but exceed thresholds of maximum or minimum production in infeasible cases.
Due to the first-in first-out allocation in the LPG', the smallest allocatable resource quantity equals the full quantity of demanded resource of a player. A LPG' player either gets its demand fully allocated, in which case it will increase its satisfaction, or it will decrease its satisfaction otherwise, since partial demand fulfilments are of no utility for it. Contrarily, a power plant has a continuous utility function with respect to allocated resources and thus

accepts arbitrarily small resource quantities in general. This would allow for a satisfaction reinforcement, proportional to the distributional deviation.
As elaborated in Section 4.4.1, the demand determination of a CPP will converge to its optimum production quantity, which is static. Based on its current production, its slope may bound the demand, which is thus time-dependent. In the LPG', players determine their need based on their available resources which themselves are randomly assigned at the beginning of each round.

## 4.4 APM allocation system: Modelling an agent-based allocation system under mission-criticality

Figure 4.2 gives an overview of the APM allocation system, whose main action sequence is outlined in as follows:
In the beginning of each round (1) each CPP $i$ within an AVPP's constituting set of power plants $CPP$ determines its demand $d_i$, as depicted in the next subsection, and publishes it. All involved measures are of course time-dependent, an additional time index is omitted though for increased readability. (2) The AVPP's allocation scheme in the scheduling process determines the current resource case based on its assigned load ($load_{res}$) and published demands of its CPPs, followed by computing an allocation $a_i$ for each CPP $i \in CPP$. This process is elaborated in Section 4.4.2. (3) Each CPP $i$ receives an allocation $a_i$ and appropriates resources in the same quantity $a'_i = a_i$, as cheating is not allowed. In the next step (4) each CPP assesses its CPP satisfaction $\sigma_i^C$ with its allocation, based on the demand-allocation-deviation, as described in Section 4.4.1. At the end of a round (5) each AVPP assesses its AVPP satisfaction in an introspective process, evaluating its fitness for purpose and triggers its dissolution in case it is not deemed to be fit for purpose. The introspection process and satisfaction aggregation is finally explained in Section 4.5.

### 4.4.1 Demand determination & deviation and satisfaction metrics

For the determination of the demand $d_i(t)$ for a CPP $i$ at time step $t$, the hard constraints minimum production and maximum production and slope of the CPP must no to be violated, as demanded by R2. Let $p_i^{min}$ denote the absolute minimum production of $i$ and $p_i^{max}$ its absolute maximum production. The slope $s_i$ bounds the output of $i$, based on its current output $p_i^{prod}(t)$, such that there exist time-dependent minimum and maximum production bounds, denoted as $p_i^{min}(t)$ and $p_i^{max}(t)$ respectively.

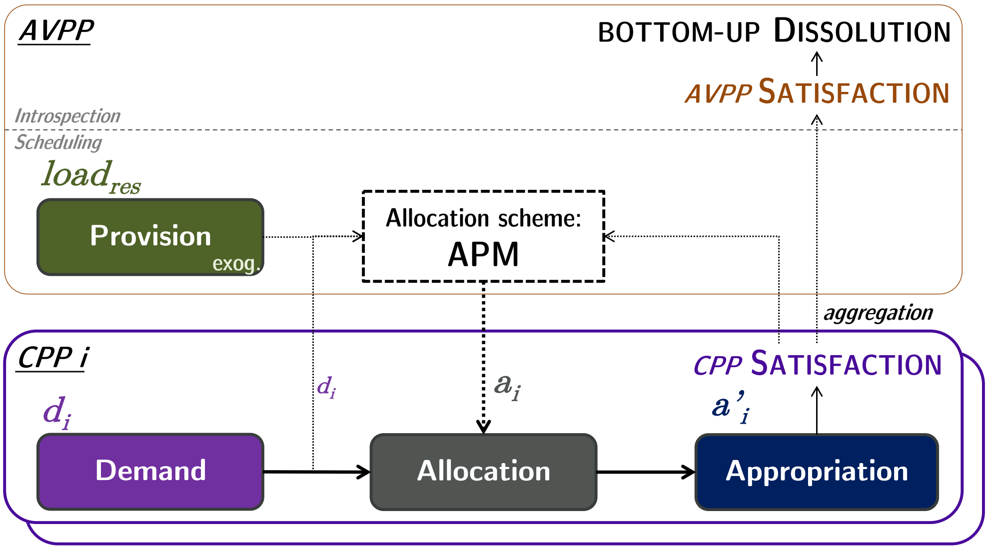



**Figure 4.2:** The APM allocation system: within the scheduling of an AVPP, its CPPs publish a demand, get an allocation from the AVPP's allocation scheme, appropriate their allocation and assess a satisfaction about the outcome. The satisfactions of the AVPP's constituting CPPs are aggregated and stipulate the AVPP satisfaction which serves as the criterion for its introspective bottom-up dissolution.

Given a current power output $p_i^{prod}(t)$, the output bounds for $t+1$ are given as

$$\begin{aligned} p_i^{min}(t+1) &= Max(p_i^{min},\ p_i^{prod}(t) - s_i) \text{ and} \\ p_i^{max}(t+1) &= Min(p_i^{max},\ p_i^{prod}(t) + s_i) \end{aligned} \tag{4.1}$$

for time-dependent minimum- and maximum production, respectively.
The static optimal production of $i$ is given by $i$'s power plant model and shall be denoted by $p_i^*$. It naturally follows $p_i^{min} \le p_i^* \le p_i^{max}$, where the optimal production depends on the power plant type and is typically close to its maximum production ($p_i^* \approx 0.95 * p^{max}$). Since every CPP strives to reach its optimum, the demand $d_i(t)$ of a CPP $i$ at time $t$ converges to $p_i^*$, but is bounded by $p_i^{min}(t)$ or $p_i^{max}(t)$ and therefore dependent on its current output. Thus, the demand is computed as:

$$d_i(t+1) = \begin{cases} p_i^{min}(t+1) & \text{if } p_i^{prod}(t) - s_i > p_i^*, \\ p_i^{max}(t+1) & \text{if } p_i^{prod}(t) + s_i < p_i^*, \\ p_i^* & \text{else} \end{cases} \tag{4.2}$$

An exemplary demand determination scenario is illustrated in Figure 4.3.

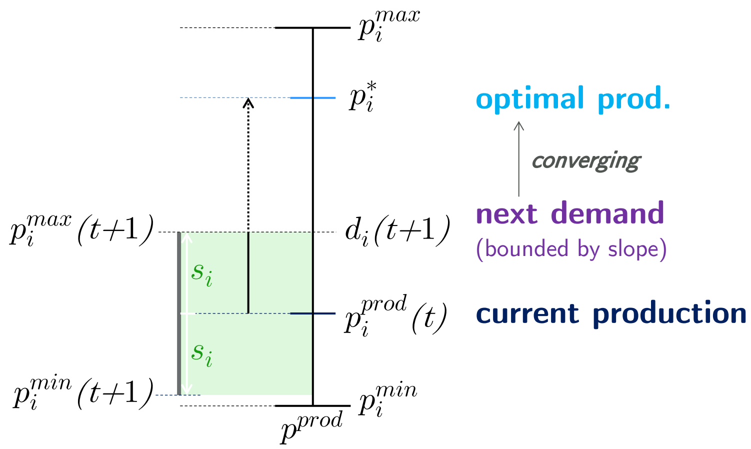



**Figure 4.3:** A CPP's demand converges to its static optimum and is bounded by its slope, resulting in time-dependent production bounds.

After all CPPs published their demands, they get an allocation form the APM allocation scheme. Starting from the trivial demand-allocation deviation $\delta_i = a_i - d_i$, where $i \in CPP$ and $a_i$ denoting the allocation of $i$, to be comparable to an other CPP, $\delta_i$ is normalised with respect to $i$'s time-dependent minimum and maximum production bounds, $p_i^{min}(t)$ and $p_i^{max}(t)$. This normalised deviation is denoted and given by:

$$\delta_i^n(t) = \frac{a_i(t) - d_i(t)}{p_i^{max}(t) - p_i^{min}(t)} \quad \text{and} \quad \delta_i^n(t) \in [0;1] \tag{4.3}$$

It is negative, if the allocation is smaller than the demand, i.e., the demand was not fulfilled, and positive, if the allocation exceeds the demand, as shown in Figure 4.4. R3' demands a sophisticated deviation metric, where, e.g., positive and negative deviations from the optimum shall have distinctive implications. Therefore, the deviation metric is modelled asymmetrically, weighting positive and negative deviations differently by introducing a factor $\omega^+ \in [0;1]$ which possibly diminishes positive $\delta_i^n$. The weighted deviation is given by:

$$\delta_i^w(t) = \begin{cases} \delta_i^n(t) \cdot \omega^+ & \text{if } \delta_i^n(t) \geq 0, \\ \delta_i^n(t) & \text{else} \end{cases} \tag{4.4}$$

Finally, a CPP $i$ assesses a subjective satisfaction $\sigma_i^C(t) \in [0;1]$ at time $t$. If the weighted deviation lays in an $\epsilon$-area around the demand, $i$ increases its satisfaction, whereas it decreases its satisfaction if the weighted deviation lays outside the $\epsilon$-area. To implement R3', the $\epsilon$-area might be skew as it is

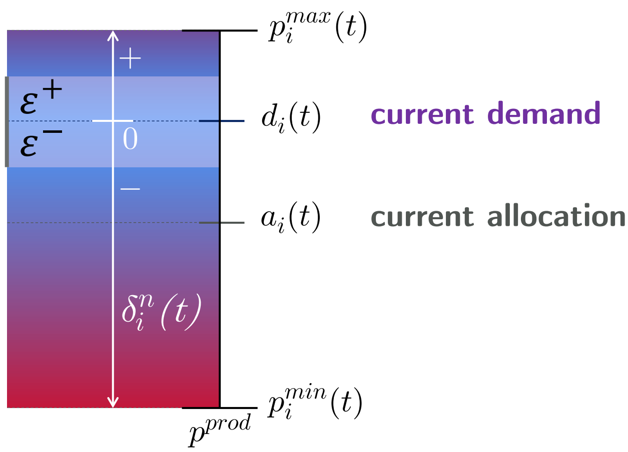



**Figure 4.4:** The allocation-demand deviation, normalised w.r.t. current minimum and maximum power production. The skewed $\epsilon$-area determines the satisfaction reinforcement.

defined by a $\epsilon^+$ and $\epsilon^-$, spanning the $\epsilon$-area around the demand, as illustrated in Figure 4.4. Ultimately, $i$ adapts its satisfaction as follows:

$$\sigma_i^C(t+1) = \begin{cases} \sigma_i^C(t) + \alpha \cdot (1 - \sigma_i^C(t)) & \text{if } \epsilon^- \leq \delta_i^w(t) \leq \epsilon^+, \\ \sigma_i^C(t) - \beta \cdot \sigma_i^C(t) & \text{else} \end{cases} \tag{4.5}$$

where $\alpha$ and $\beta$ are coefficients $\in [0;1]$ which determine the rate of reinforcement of satisfaction and dissatisfaction respectively.

### 4.4.2 Resource case determination and Allocator sequence derivation

After getting all demands from the constituting CPPs in the AVPP's scheduling process, the given residual load is to be fully allocated to the CPPs. The APM allocation scheme therefore determines the current situation regarding resource economy by comparing the exogenous resource provision, i.e., the residual load $load_{res}(t)$, with the published demands and both maximum and minimum production capacities. It then determines the individual allocations, congruent to the resource case, which implements Ostrom principle P2, and thus partially fulfils R2.

Let $D(t)$ denote the total quantity of demanded resources, given by

$$\begin{aligned} D(t) &= \sum_{i \in CPP} d_i(t) \quad \text{and analogously} \\ P^{min}(t) &= \sum_{i \in CPP} p_i^{min}(t) \;\; \text{and} \\ P^{max}(t) &= \sum_{i \in CPP} p_i^{max}(t) \end{aligned} \tag{4.6}$$

for the time-dependent total minimum and maximum production capacity, respectively. To determine the state of resource economy, the following measures are defined:

$$\begin{aligned} \Delta_u(t) &= load_{res}(t) - \sum_{i \in CPP} p_i^{max}(t) = load_{res}(t) - P^{max}(t) \\ \Delta_l(t) &= load_{res}(t) - \sum_{i \in CPP} p_i^{min}(t) = load_{res}(t) - P^{min}(t) \\ \Delta_d(t) &= load_{res}(t) - \sum_{i \in CPP} d_i(t) = load_{res}(t) - D(t) \end{aligned} \tag{4.7}$$

An exhaustive enumeration of resource cases is given in Figure 4.5 and listed in the following. Infeasible resource cases cause a violation $v(t) = p_i^{prod}(t) - load_{res}(t)$, as either not the complete residual load is assignable or there is more production than residual load.

- $\Delta_u(t) \geq 0 \;\Leftrightarrow\; load_{res}(t) \geq P^{max}(t)$:
  All CPPs produce their **maximum production** quantity
  (i.e., $p_i^{prod}(t) = p_i^{max}(t) \; \forall i \in CPP$)

  - $\Delta_u(t) > 0$:
    **Upperbound infeasible**: Although all power plants are allocated their maximum output, the residual load cannot be fulfilled, it is lower deviated, leading to $v(t) < 0$ (under-production).
  - $\Delta_u(t) = 0$:
    **Upperbound feasible**: The residual load is exactly met at maximum total production (unlikely), $v(t) = 0$.

- $\Delta_l(t) \leq 0 \;\Leftrightarrow\; load_{res}(t) \leq P^{min}(t)$:
  All CPPs produce their **minimum production** quantity
  (i.e., $p_i^{prod}(t) = p_i^{min}(t) \; \forall i \in CPP$)

  - $\Delta_l(t) < 0$:
    **Lowerbound infeasible**: Although all power plants are allocated their minimum output, the residual load is exceeded, leading to $v(t) > 0$ (over-production).

- $\Delta_l(t) = 0$:
  **Lowerbound feasible**: The residual load is exactly met at minimum total production (unlikely), $v(t) = 0$.

- $\Delta_u(t) < 0 < \Delta_l(t) \Leftrightarrow P^{min}(t) < load_{res}(t) < P^{max}(t)$:
  There is a **variability** in the allocation: CPPs get individual allocations within their feasible production range, $v(t) = 0$.
  (i.e., $p_i^{min}(t) < p_i^{prod}(t) < p_i^{max}(t)\ \forall i \in CPP$)
  - $\Delta_d(t) < 0$:
    **Variable scarcity**: The residual load is exactly met and lower deviates the total demand $D(t)$, i.e. there is a resource scarcity.
  - $\Delta_d(t) = 0$:
    **Variable exact**: The residual load is exactly met and exactly meets the total demand (unlikely).
  - $\Delta_d(t) > 0$:
    **Variable surplus**: The residual load is exactly met and exceeds the total demand, i.e. there is a resource surplus.

The APM allocation scheme implements a set of allocators, to cover specific resource case aspects. Depending on the resource case, a single allocator or a sequence of allocators is used to define the ultimate allocations. The resource case allocator mapping or allocator sequence derivation is shown in Figure 4.5. In case of the *upper bound* resource cases, the MAXall allocator allocates resources equal to the CPPs' time-dependent maximum production quantity ($a_i(t) = p_i^{max}(t) \forall i \in CPP$). Analogously, the MINall allocator allocates minima for the *lower bound* resource cases ($a_i(t) = p_i^{min}(t) \forall i \in CPP$).
In case of the *variable* resource cases, i.e. variable allocations, first the MINall is applied in all subcases as a base allocation, adhering the satisfaction of the minimum production constraint. If there is an economy of resource scarcity in the *variable scarcity* case, where the CPPs are in competition to get resources allocated, the APM LC allocator, implementing a fair legitimate-claims based allocation, is used. The APM LC allocator is explained in Section 4.4.3. If the residual load equals the sum of demands, in the *variable exact* resource case, the DEMANDall allocator allocates resources such that the total allocated resources, including those from MINall before, equal the CPPs' demand ($\sum_{a_i(t)} = d_i(t) \forall i \in CPP$). For the *variable surplus* case, DEMANDall is applied. As any further allocation is then detrimental for a CPP, because it already got its demand fulfilled, the APM LC allocator is applied in *inverse mode*, where allocations are considered detrimental, not beneficial, for a CPP. All allocators adhere also the maximum production constraint. In the APM LC, a CPP's merit based on its claims may be high enough to get an allocation which would exceed its maximum production. In such cases, there is a 'residual residual' load which is reallocated to other CPP's utilising the APM LC anew.

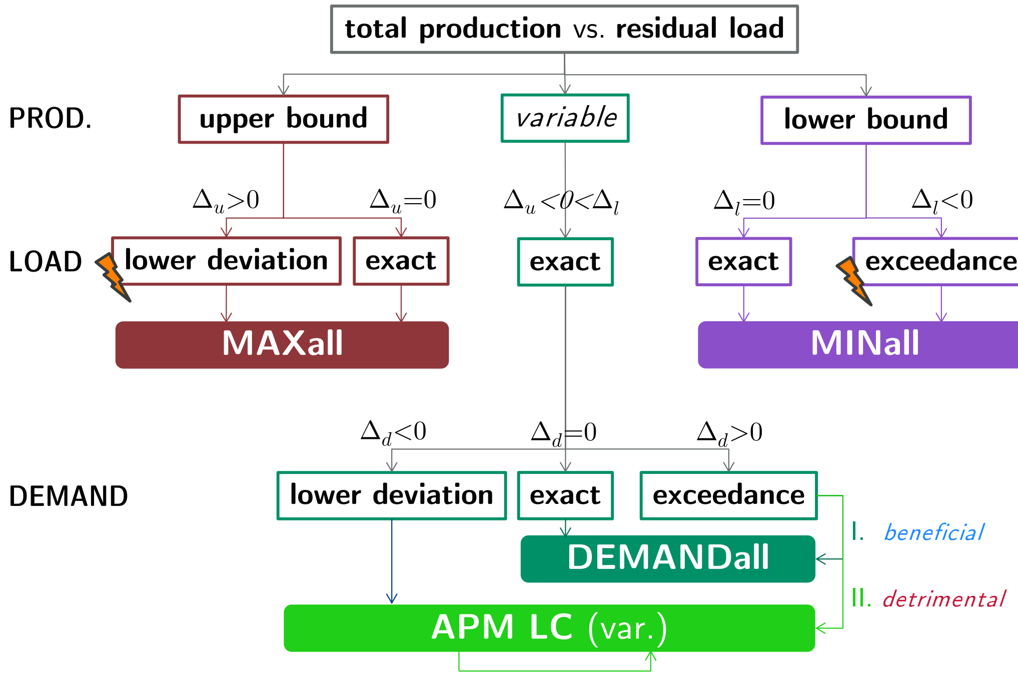



**Figure 4.5:** Resource cases and allocator mapping: resource cases are identified using Equation 4.7 and mapped to allocators as shown.

### 4.4.3 APM Legitimate Claim Allocator incorporating Canons of Distributive Justice

The APM LC allocator allocates resources proportional to a CPP's demand and its legitimate claims, valuated in form of particular canons of distributive justice for APM resource allocation. It also considers if allocations are beneficial or detrimental for a CPP, i.e., whether a CPP's intermediate allocation lower deviates or exceeds its demand, respectively. The latter case, where further allocations are detrimental shall be denoted by *inverse mode*. Thus within APM LC, fair allocations can be guaranteed, as demanded by R3.

As the power plants are highly heterogeneous, special attention has to be paid to equalise the CPP treatment by adequately comparing individual CPPs. For instance, both the demand and maximum production of different CPPs may differ significantly, even by several orders of magnitude, comparing, e.g., comparing a nuclear power plant with a small community-drive bio-gas power plant. The relative demand $d_i^r(t) \in [0;1]$ of a CPP $i \in CPP$ at time $t$, is given by

$$d_i^r(t) = \frac{d_i(t)}{\sum_{j \in CPP} d_j(t)}, \text{ with } \sum_{i \in CPP} d_i^r(t) = 1 \tag{4.8}$$

Like in the LPG', canons are used to determine rank lists, reflecting the power plant's relative merits but based on APM specific canons here. As the allocations are dependent on the resource case, which differs in the APM for different rounds, the canons are based on statistical data about a certain time-range of past rounds, denoted by `windowSize`. Note that with the windowed statistics approach, the APM LC also incorporates the social principle of *forgiveness*, though it is based on passive 'forgetness' rather than proactive forgiveness.

- $f_1$: **The canon of equality**
  As described before, this canon equalises heterogeneous CPPs by firstly ranking the CPPs in decreasing order of their average absolute weighted deviation $|\delta_i^w|$. Secondly ranking in increasing order of their satisfaction $\sigma_i^C$ and thirdly in increasing order of the number of rounds in which they received an allocation.
- $f_2$: **The canon of needs**
  Rank the CPPs in decreasing order of their average relative demand $d_i^r$.
- $f_3$: **The canon of productivity**
  Rank the CPPs in decreasing order of their reliability trust value.
- **The canon of effort** is meaningless in the APM context and thus unrepresented.
- $f_5$: **The canon of social utility**
  Rank the CPPs in decreasing order of their credibility trust value.
- **The canon of supply and demand** is inappropriate in the APM context and thus unrepresented. Though, for further work it might be adequate to incorporate the power plant type in this canon.
- **The canon of merits and achievements** is meaningless in the APM context and thus unrepresented.

The computation of the ranking lists and resulting total Borda score $B(i, F)$, analogously to the LPG' as given in Equation 3.3, is the first step (1) of the APM LC allocator. In the *inverse mode* APM LC, the ranking lists are reversed, transforming positive to negative claims and vice versa. Because there are always preceding allocators to APM LC, the residual load has to be deduced by further allocations (2), denoted by intermediate allocation and given as:

$$a_i^{\sim}(t) = \sum_{a \in A} a_{i,a}(t) \tag{4.9}$$

where $A$ is the set of allocators and $a_{i,a}(t)$ denotes the allocation for CPP $i$ from allocator $a$ at time $t$. The resulting updated residual load is given by $load^{\sim}_{res}(t) = load_{res}(t) - \sum_{i \in CPP} a^{\sim}_i(t)$. Analogously, the maximum production bounds have to be updated, also considering intermediate allocations: $p^{max\sim}_i(t) = d_i(t) - a^{\sim}_i(t)$. Note that the minimum production bound has not to be considered, as MINall already adhered the satisfaction of this constraint. In *inverse mode*, the maximum production bound is given as $p^{max\sim}_i(t) = p^{max}_i(t) - a^{\sim}_i(t)$.

The main approach of the APM LC is to determine allocations proportional to both relative demand $d^r_i$ and total Borda score $B(i, F)$ of a CPP $i$ based on the residual load, in contrast to the Borda queue first-in first-out allocation in the LPG'. The relative demand is incorporated in the proportional allocation, as a compensation for the equalisation within the equality canon, considering the CPP heterogeneity as described before. The bounded allocation of APM LC for a CPP i at time $t$ is computed as

$$a_{i,LC}(t) = Min\left[\underbrace{p^{max\sim}_i(t)}_{\text{upper bound}},\ \underbrace{load^{\sim}_{res}(t) \cdot \left(\omega_d \cdot d^r_i(t) + \omega_{lc} \cdot B^n(i, F)(t)\right)}_{\text{proportional allocation}}\right] \tag{4.10}$$

where $\omega_d$ and $\omega_{lc}$ are weights $\in [0; 1]$, for the relative demand and the legitimate claims respectively, which allows balancing, and $B^n(i, F)(t)$ is the normalised total Borda score given as

$$B^n(i, F)(t) = \frac{B(i, F)(t)}{\frac{n\,(n+1)}{2}}\text{, where } n = |CPP| \tag{4.11}$$

If an allocation would exceed the upper bound, the exceeding resource quantity is accrued in a resource pool which is distributed by a new APM LC instance, following the same process as described above. As this instance, again, might leave a 'residual residual' load, the APM LC is applied until the residual resources are completely allocated, i.e., the pool is depleted, which is guaranteed.

## 4.5 AVPP-satisfaction and -dissolution mechanism

In the intra-organisational self-evaluating, introspective adaptation mechanism of the modified APM scheduling, as presented above, an AVPP, i.e., an organisation, assesses a satisfaction, to be used as a fitness-for-purpose evaluation criterion. Based on the evaluation of the criteria, an AVPP may trigger its dissolution, to get reformed in form of a reorganisation, where the constituents of the AVPP change, as described in Section 2.3. In the modified scheduling, the dissolution criterion is solely defined as the above-mentioned AVPP satisfaction and given as an aggregation of its constituting CPPs' satisfactions. An AVPP

$a$, grouping a set of CPPs ($CPP$) assesses its satisfaction $\sigma_a^A(t)$ at time $t$ as the arithmetic mean:

$$\sigma_a^A(t) = \frac{1}{|CPP|} \sum_{i \in CPP} \sigma_i^C(t) \tag{4.12}$$

Technically, the dissolution is implemented, using a *time frame constraint* which checks for a lower deviation of a given minimum satisfaction threshold and triggers the reformation if the constraint is violated a given number of times within a given time interval (time frame). Thus, occasional violations do not trigger the disruptive and computing-time intensive reformation process.

Since the dissolution only depends on a property of the constituting CPPs, this kind of dissolution is considered to be a *bottom-up dissolution*, although the constituting CPPs do not pro-actively trigger the dissolution of their AVPP, but the AVPP itself recognises the bottom-up dissolution by introspection.
In further work, a multi-criteria dissolution mechanism might be implemented, raising the need for conflict resolution in the case of conflicting bottom-up and top-down dissolution decisions, where the latter might, e.g., evaluate scheduling violations or trust values on the meso-level. One reconciliation approach at hand would be the implementation of a collective-choice agreement through, e.g., voting, while further promoting endurance through the application of Ostrom principle P3.

# Chapter 5

# Empirical Validation of CPR Scheduling & Interference Pattern Analysis

In this chapter, the CPR-based scheduling is evaluated empirically by an analysis of its performance with respect to the APM's macro-level goals and the expected promotion of both fairness and satisfaction, while the structural adaptation mechanisms are deactivated. The results are then compared with the traditional CSOP scheduling. General system characteristics, as relevant for the scheduling process, are identified and serve as an evaluation basis for further analyses. As the satisfaction is the main criterion for the AVPP dissolution, its time-dependent development is investigated as is the influence of the AVPP composition on its satisfaction fluctuation. This investigation also yields the identification of criteria for suitable AVPP formation aiming at high mean satisfaction and low satisfaction fluctuation. A short analysis on scheduling runtime behaviour and claim-weight development is performed, before interference patterns due to the interleaving of structuration adaptation mechanisms are qualitatively analysed in the second part of this chapter. Therein, firstly the operation of the hierarchical adaptation mechanism is investigated in isolation, while the dissolution is deactivated. A stable state being quickly reached is expected, since the adaptation is only triggered by scheduling times which only change if AVPPs get reformed in case of an AVPP dissolution. This investigation is followed by an isolated investigation of the reformation mechanism, focussing on emerging oscillations and patterns and the suitability of the adaptation mechanism, evaluated through structural long-term stability. In a last step, both structural adaptation mechanisms are activated concurrently and interferences between these adaptation mechanisms are investigated as are their trigger frequencies and termination behaviour and thus their influence on the system performance in terms of stability.

## 5.1 Evaluation methodology & parameter configuration

The investigations are empirically performed, using an existing implementation of the APM with the modified scheduling based on self-organising legitimate-claims CPR allocation. The data for the investigations of a simulation run with a predefined number of simulation time steps (ticks) are captured on three different levels of observation and are aggregated accordingly:

1. **System level** (macro)
   The following relevant data are captured at the system level in *each tick*:

   (a) The **total consumption-production gap** measures the actual deviation of total produced power, both from CPPs and SPPs, and power consumption (load) for each tick. Scheduling violations are thus one factor of this gap which itself mainly determines the power grid frequency deviation. It thus depicts the main measure for the system stability, bearing in mind that the scheduling is but only one component of this gap.

   (b) The system's total residual load is assigned to and captured as **top-level AVPP residual load**.

   (c) Statistical data of the **satisfactions and deviations** are aggregated from the hierarchy layer levels. They thus capture and aggregate all AVPP and CPP satisfaction and deviation (see below).

   (d) **Adaptation event count** data counts the total amount of triggered actions per adaptation mechanism of all AVPPs.

   (e) The **hierarchy depth** depicts the diameter of the AVPP graph, i.e., the maximum number of AVPPs from the top-level AVPP to a Physical Power Plant (PPP).

2. **Hierarchy layer level** (meso)
   The hierarchy layer level data are captured orthogonal on the AVPP hierarchy, aggregating the following data of structural elements, i.e. both AVPPs and CPPs, on the same hierarchy level, for *each tick and hierarchy level*:

   (a) Statistical data of the **satisfactions and deviations** are aggregated from the structural elements on the same layer. They thus capture and aggregate all AVPP- and CPP satisfactions and deviations.

   (b) **Adaptation event count** data counts the amount of triggered actions per adaptation mechanism of AVPPs on the same layer.

3. **AVPP level** (micro)
   On the AVPP level, data is gathered for *each tick and AVPP*. The most important gathered data are as follows:

   (a) The **scheduling duration** measures the runtime of the scheduling process which is used to trigger layer actions of the meso-level structuration mechanism.

   (b) Statistical data of **satisfaction and deviation**. These data capture aggregations of AVPP's constituents satisfaction ($\sigma^A$) and their deviation data. Note that since in each tick, the scheduling is performed for a given number of `lookahead steps`, each step produces scheduling data like satisfaction and deviation. This data from the individual lookahead scheduling steps are aggregated and assessed as averages for each tick.

In order to get statistically sufficient data, each *experiment*, i.e. simulation with specific predefined parameter configuration, is repeated $n$ times, constituting a sample set of *experiment run*s with sample size $n$. Thus, within an experiment evaluation on system-scope, four kinds of aggregation are performed:

1. **Run aggregation** to aggregate the individual runs to a single run, computing the average and standard deviation for each value type of all runs. The standard deviation of a value type expresses the variation of the values of that value type over the individual runs.

2. **AVPP aggregation** as described above, to aggregate AVPP-scope values to a single mean value for each tick, also assessing the standard deviation as a measure for the deviation of the individual AVPPs.

3. **Tick aggregation** to aggregate tick values to a single value for each experiment run, assessing average and standard deviation for each value, where the standard deviation expresses the variation of the individual ticks.

4. **Lookahead aggregation** to aggregate scheduling-related data from each individual lookahead step within the scheduling of an AVPP, where the data of each step are averaged and fed-back to the APM tick time base.

To express the overall deviation of a system-scope value type over the individual runs, like in Table 5.3, within the tick aggregation, the standard deviation values for the value types, obtained as outcome of the run aggregation, are aggregated through averaging, resulting in the average standard deviation measure. This measure expresses the average standard deviation of a value type over the runs over the ticks.

Table 5.1 gives an overview over the **numerical experiment parameters**. Due to the huge parameter configuration space a suitable *standard parameter configuration* was determined empirically in a sensitivity analysis as $C_S$, shown in Table 5.1. Obviously, the crucial parameters regarding AVPP reformation behaviour are the `minimum satisfaction threshold`, and the deviation thresholds $\epsilon^+$ and $\epsilon^-$ for the satisfaction reinforcement. Higher `statistic window sizes` delay AVPP dissolution decisions through averaging over a higher number of relevant values and thus stipulate a tolerance mechanism, whereas the reinforcement rates $\alpha$ and $\beta$ affect the dissolution frequency anti-proportionally. Unless stated otherwise, $C_S$ is used throughout the experiments. Additionally to the numerical parameters, the most important **categorical experiment parameters** are whether the adaptation mechanisms are enabled or disabled, which type of claim-weight determination is used and how the initial AVPP meso-level hierarchy is determined. Configurations with disabled structural adaptation mechanisms are denoted *static*, since the hierarchy is not changed throughout a run, contrasting to a *dynamic* configuration, where at least one structural adaptation mechanism may alter the hierarchy. The **initial hierarchy** determines the number of AVPPs and their compositions. It may either be a pre-defined structure, or formed through a random structuration process, in which power plants are randomly assigned to AVPPs, whose number is also randomly determined. In the latter case, each experiment would base on a distinctive initial hierarchy obviously. The set of PPPs, including their models, is pre-defined and equally used in each experiment. The categorical parameter configuration is stated for each experiment.

The APM AVPP hierarchy is technically modelled as a tree-structured partitioning graph, with a top-level element denoted as *top-level AVPP*. Each AVPP node has to have child elements, which may either be (virtual) AVPPs or Physical Power Plants (PPPs) nodes, whereas the leaves have to be PPPs, i.e. CPPs or SPPs. Edges denote constitution or subordination relations for respective bottom-up or top-down direction. Hierarchies consisting of only one layer of intermediary AVPPs (constituting the top-level AVPP) and PPPs as leaves on the bottom-layer shall be denoted as *flat*, opposed to *hierarchical* structures. A special case of a flat hierarchy is the *grand coalition*, where all PPPs are subordinated to one single AVPP which itself is subordinated to the top-level AVPP. The pre-defined initial flat hierarchy $H_{flat}$ consists of 9 partitions and thus 10 AVPPs, including the top-level AVPP and a total of 523 PPPs (350 SPPs, 173 CPPs). A pre-defined hierarchical hierarchy of depth 5 is given as $H_{hier}$. The number of participating power plants in the scheduling of an AVPP, i.e., its numbers of constituting CPPs and AVPPs with subordinated CPPs, is denoted by $p$.
Similar to (Pitt, Schaumeier, Busquets & Macbeth 2012), fairness shall be denoted as statistical dispersion of AVPP satisfaction. It is measured as the Gini

**Table 5.1:** Summary of numerical experiment parameters for the respective APM and LPG' subsystems and empirically determined suitable standard parameter configuration.

| System | Subsystem | Parameter | Value $C_S$ |
|---|---|---|---|
| APM | Scheduling | `lookahead steps` | 4 |
| | Adaptation (reform.) | `statistics window size` | 10 |
| | | `min. satisfaction threshold` | 0.2 |
| | | `max. violations` | 5 |
| | | `timeframe` | 10 |
| | Adaptation (layer) | `min. scheduling duration` | 20ms |
| | | `max. scheduling duration` | 150ms |
| LPG' | legitimate claims | `statistics window size` | 10 |
| | APM allocation | $\omega_d$ | 0.2 |
| | | $\omega_{lc}$ | 0.8 |
| | deviation | $\omega^+$ | 0.5 |
| | satisfaction | $\epsilon^+$ | 0.2 |
| | | $\epsilon^-$ | -0.2 |
| | | $\alpha$ | 0.1 |
| | | $\beta$ | 0.1 |

inequality coefficient $G(t) \in [0;1]$ over the AVPP satisfactions $\sigma_a^A(t), a \in AVPP$. $G(t) = 0$ indicates maximum fairness at tick $t$, i.e., the satisfaction of all AVPPs are equal, whereas $G(t) = 1$ depicts minimum fairness, i.e., maximum dispersed AVPP satisfactions. (Gini 1912)

Table 5.2 lists all experiments, which are structured in experiment sets according to their respective analysis. The respective sample set size $n$, scheduling implementation, initial structure type and determination as well as numerical parameters, if differing from the standard configuration $C_S$, are stated in Table 5.2 for each experiment. Note that not all analyses are listed though since some experiments use data from other experiments.

## 5.2 Scheduling performance evaluation and comparison & system characteristics with static AVPP-hierarchy

The first experiment set ($ES_1$) evaluates the performance of the LPG' scheduling on the system scope by comparing it to the CSOP-based scheduling firstly in terms of consumption-production gap and secondly by the resulting total satisfaction. To ensure comparability at first glance the first two experiments

**Table 5.2:** Evaluation experiment overview table: The experiments of respective analyses are structured in experiment sets. The respective sample set size $n$, scheduling implementation, initial structure type and determination as well as numerical parameters, if differing from the standard configuration $C_S$, are stated for each experiment. Dashes indicate a respectively disabled adaptation mechanism.

| E | n | Sche-duling | Flat/ Hier. | Pre-def./ Random | `Min. Sched. Duration` | `Max. Sched. Duration` | `Min. Satisf. Thresh.` |
|---|---|---|---|---|---|---|---|
| $\boldsymbol{ES_1}$ Performance & Dev.-Sat. Evaluation (Ch. 5.2, 5.3) | | | | | | | |
| $E_{1,C}$ | 10 | CSOP | flat | $H_{flat}$ | – | – | – |
| $E_{1,L}$ | 10 | LPG | flat | $H_{flat}$ | – | – | – |
| $E_{1,LR}$ | 50 | LPG | flat | random | – | – | – |
| $\boldsymbol{ES_2}$ Isolated Meso-level Adaptation (Ch. 5.4) | | | | | | | |
| $E_2$ | | LPG | flat | $H_{flat}$ | 20ms | 150ms | – |
| $\boldsymbol{ES_3}$ Isolated Micro-level Adaptation (Ch. 5.4) | | | | | | | |
| $E_3$ | 10 | LPG | flat | random | – | – | 0.2 |
| $E_4$ | 4 | LPG | flat | random | – | – | 0.5 |
| $E_5$ | 8 | LPG | hier. | random | – | – | 0.5 |
| $E_6$ | 14 | LPG | hier. | $H_{hier}$ | – | – | 0.5 |
| $\boldsymbol{ES_4}$ Concurrent interleaving Adaptations (Ch. 5.5) | | | | | | | |
| $E_7$ | 10 | LPG | flat | $H_{flat}$ | 35ms | 150ms | 0.5 |
| $E_8$ | 10 | LPG | hier. | $H_{hier}$ | 35ms | 150ms | 0.5 |
| $E_9$ | 20 | LPG | hier. | random | 35ms | 150ms | 0.5 |

of $ES_1$ use the flat pre-defined initial hierarchy $H_{flat}$.
Figure 5.1 shows **residual load and mean production-consumption gap** time-curves of $ES_1$ for CSOP scheduling in $E_{1,C}$, where the CPLEX optimiser is used to solve the CSOP, and LPG' scheduling in $E_{1,L}$. Both experiments are repeated $n = 10$ times and run 500 ticks in each run. The first general system characteristic to notice is that the residual load has equal time profiles irrespective of the scheduling algorithm, since it is determined through predicted total load and predicted SPP production, which both base on historical data and random elements, which are however equal for equal simulation seeds. Thus the variation of the residual load between the runs is 0. Another identifiable system characteristic is an oscillation of the residual load with a cycle length of $T = 96$ ticks, indicated through dashed lines in Figure 5.1. The cycle profiles are quantitatively identical. Because the residual load is the main input of the scheduling, its oscillation is reflected in the production-consumption gap, though only the cycle length is reflected. Qualitative time-curve correlations between residual load and gap cannot be concluded. Also the gap cycle profiles are only qualitatively similar to each other. In the first half of a cycle, the mean gap of CSOP scheduling is around 0kW, whereas in LPG' scheduling it is considerably higher, around -50,000kW. Interestingly, their mean gaps are very similar to each other in the second part of a cycle. The average values of residual load and gap over all ticks can be found in Table 5.3. The average gap of the LPG' scheduling is about 14 times higher than the CSOP scheduling gap. However, the average standard deviation of the mean gap over the individual runs is with approximately 3121kW for the LPG' scheduling only about the half of the CSOP scheduling. Overall the LPG' scheduling seems to be suitable to replace the CSOP-based scheduling. Its lower performance regarding production-consumption gap was expected through the sacrification of the CSOP's optimality. A dedicated investigation about the reasons for the higher mean gap as well as its implication for the power grid may be part of further work.

As performance deviations from the optimal CSOP scheduling in terms of gap and frequency deviation was expected, as described in Section 4.3, the next experiment compares the respective scheduling performances with respect to resulting **satisfaction and fairness** which was the main criterion for the incorporation of a fair LPG' allocation based scheduling. As shown in Table 5.3, LPG' scheduling considerably outperforms CSOP scheduling with approximately 4.3 times higher mean satisfaction and 4.6 times higher fairness. The satisfactions of the LPG' scheduling ranges within $[0.48; 1]$ opposed to the CSOP extrema of 0 and 0.57. A qualitative illustration of the satisfaction dispersion is given in Figure 5.2.
In $E_{1,LR}$, the initial flat structure is determined randomly with a random number of partitions, ranging from 1 (grand coalition) to 50. The sample size

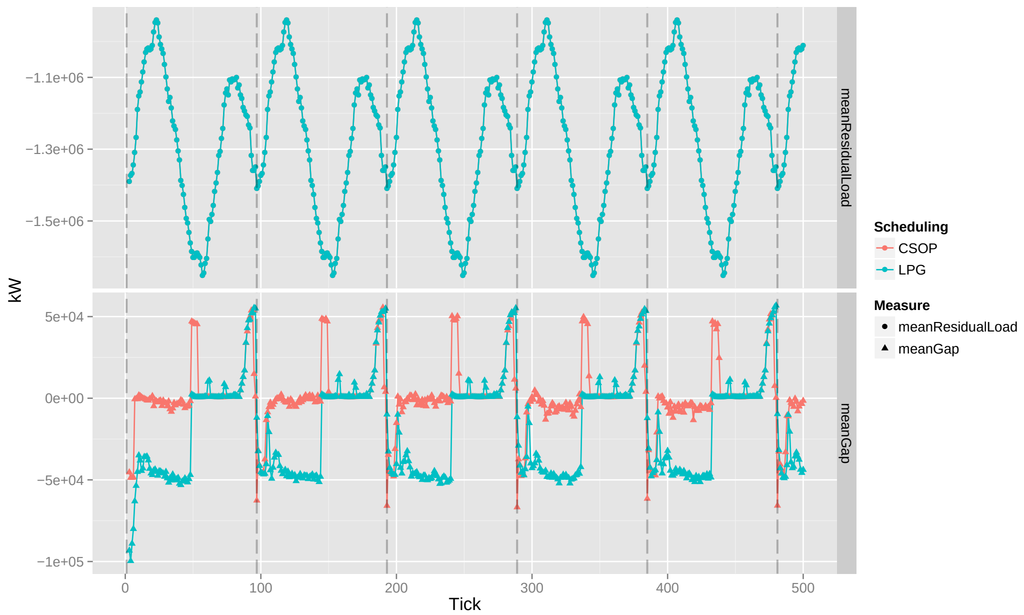



**Figure 5.1:** Residual load and consumption-production gap time-curves of $ES_1$ on the system-scope. The values are computed for $E_{1,C}$ and $E_{1,L}$ through run-aggregation. Oscillations in both residual load and consumption-production gap are identifiable and indicated through dashed lines. Where the residual load is identical in each cycle and run and thus independent of the scheduling approach, the mean consumption-production gap is scheduling approach dependent and higher in the LPG'- than in the CSOP scheduling.

**Table 5.3:** CSOP- and LPG' scheduling comparison conclusion table of $ES_1$. AVPP-scope values like satisfaction and Gini coefficient, expressing fairness, are averaged over all AVPPs. As described in Section 5.1, tick mean and standard deviation depict statistics of the tick aggregation, whereas the average standard deviation of the aggregation over the runs expresses the deviation between individual experiment runs. CSOP scheduling outperforms LPG' scheduling in terms of consumption-production gap and vice-versa for satisfaction and fairness, expressed by the Gini inequality coefficient. This also holds for $E_{1,LR}$ with a random flat structure, where the number of AVPPs is random between 1 and 50, after the top-level AVPP. The deviations between the runs are overall very low.

| | Tick Aggr. | | Run Aggr. |
|---:|---:|---:|---:|
| | Mean | SDev | Avg. SDev |
| Residual load | -1,270,721.841 | 197,500.471 | 0 |
| CSOP ($E_{1,C}$) | | | |
| Prod./Cons. gap | -1,398.129 | 45,441.299 | 6,119.164 |
| Satisfaction | 0.200 | 0.155 | 0.032 |
| Gini coefficient | 0.438 | 0.090 | 0.025 |
| LPG' ($E_{1,L}$) | | | |
| Prod./Cons. gap | -20,198.956 | 49,915.744 | 3,121.161 |
| Satisfaction | 0.864 | 0.152 | 0.007 |
| Gini coefficient | 0.095 | 0.031 | 0.002 |
| LPG' ($E_{1,LR}$) | | | |
| Prod./Cons. gap | -21,232.648 | 49,968.033 | 4,266.253 |
| Satisfaction | 0.832 | 0.176 | 0.111 |
| Gini coefficient | 0.104 | 0.031 | 0.089 |

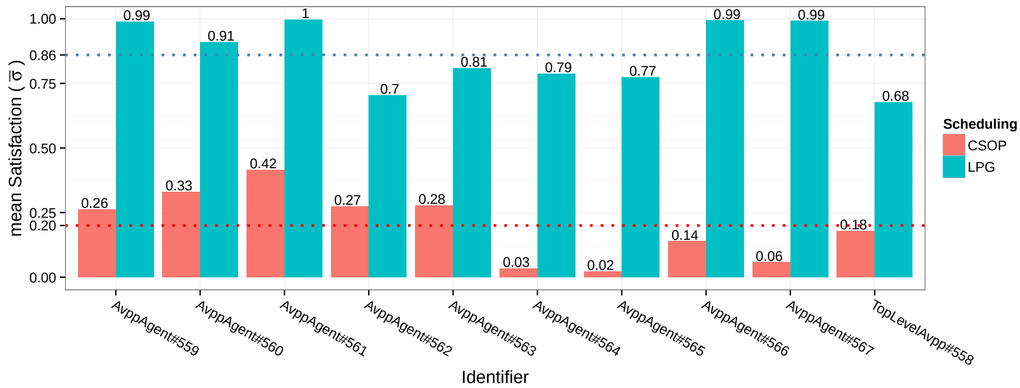



**Figure 5.2:** Illustration of satisfaction dispersion as explanation for respective Gini coefficients on the AVPP-scope of $ES_1$ for CSOP and LPG' scheduling. The plot data are obtained through run- and tick-aggregation of $E_{1,C}$ and $E_{1,L}$. Mean satisfaction values are indicated through dashed lines respectively.

of $E_{1,LR}$ is $n = 50$. As presented in the conclusion table, the performance of LPG' scheduling is stable also for random initial structures, while the average standard deviation of the runs is increased, as expected due to varying initial structures. Justified by the overall very low run deviations, smaller sample sizes are used in further experiment sets.
Time-dependent fluctuations of both satisfaction and Gini coefficient are shown in Figure 5.3. As quantitatively stated in the conclusion table, the standard deviations of the scheduling approaches are similar but the Gini coefficient standard deviation of the LPG' scheduling is smaller. Again, an oscillation is observable. The amplitude of an oscillation cycle is anti-proportional to the respective cycle of the residual load oscillation. A refined analysis of the satisfaction development on AVPP scope, investigating the oscillation reflection, is given later in Section 5.3.

A brief analysis of the runtime behaviour is given in the following, due to its importance as the trigger criterion in the meso-level structuration adaptation. Where the runtime behaviour of the CPLEX as CSOP solution algorithm does not show significant fluctuations, the runtime of the LPG' scheduling fluctuates significantly. The LPG' runtime behaviour has shown to be linear in the number of participants for small $p < 173$, in an analysis based on the data of $E_{1,LR}$. Assuming this linear runtime behaviour, the average time coefficient for one participant can be determined as approximately 5.5ms, with an average standard deviation of approximately 1.4ms. This high standard deviation has significant implications: for an exemplary run within $E_{1,LR}$ with $p = 45$, the scheduling runtime with a mean value of 208ms varies with a standard deviation

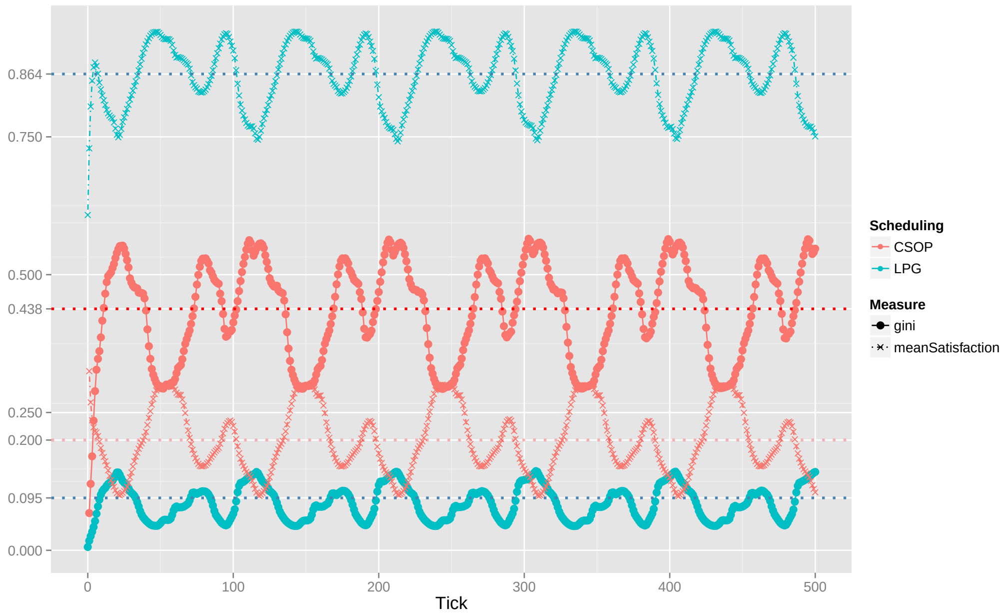



**Figure 5.3:** Satisfaction and Gini coefficient time-curves on the system-scope of $ES_1$ for CSOP and LPG' scheduling, showing oscillations, anti-proportional to the residual load oscillation. The plot data are obtained through AVPP and run-aggregation of $E_{1,C}$ and $E_{1,L}$. Mean values are indicated through dashed lines respectively. The LPG' scheduling results in considerably improved satisfaction and fairness levels.

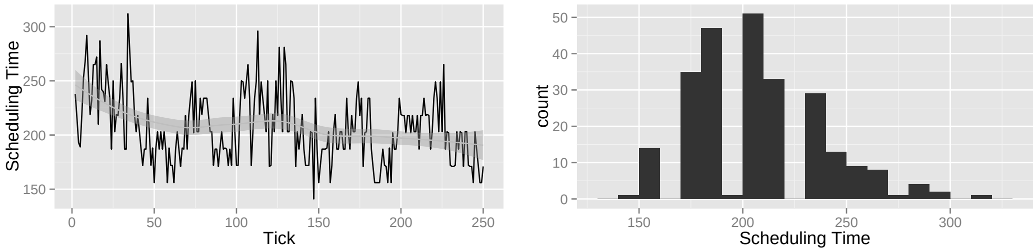



**Figure 5.4:** Typical scheduling time fluctuation of an AVPP with 45 schedulable power plants in the LPG' scheduling.

of 35ms, by up to 55% in positive direction (max. ≈ 322ms) and up to 33% in negative direction (min. ≈ 137ms), as exemplarily shown in Figure 5.4. These deviation figures are typical and occur very frequently for all $p$, such that the LPG' overall scheduling runtime behaviour is highly fluctuant, thus impairing its role as trigger for an adaptation mechanism, where each unnecessary adaptation due to fluctuations is detrimental due to its disruptiveness and computing resource demand. The fluctuations are presumably caused by the rule engine intensively in use in the LPG' operation.
To overcome this issue, the LPG' runtimes in the APM scheduling are overridden using a fixed time-coefficient with an added Gaussian error ($\mu$ = 5.5ms, $\sigma$ = 0.05ms), to mimic realistic minor deviations.

## 5.3 Deviation-Satisfaction correlation on AVPP level & satisfaction-promoting AVPP formation criteria

In this section, the time-dependent satisfaction development and its correlation to deviation and residual load as well as the interference of claim feedback and claim weighting are investigated. Due to the importance of the satisfaction measure in the AVPP dissolution mechanism, special attention is laid on fluctuations aiming on identifying suitable criteria for AVPP formation. The data in use are run aggregations of the $E_{1,L}$ data, with the fixed initial hierarchy $H_{flat}$. Note that scheduling data on the AVPP level are obtained through averaging over the lookahead steps within the scheduling.
Figure 5.5 shows the deviation and satisfaction curve of an exemplary AVPP within $H_{flat}$. An AVPP's deviation is defined as the mean of its constituting CPPs' absolute weighted deviation $|\delta_i^w|$ (Eq. 4.4) and is shortly referred to as deviation in this analysis. Analogously, the regarded AVPP satisfaction is given as the mean of the CPP satisfactions of an AVPP (Eq. 4.12). The residual load is superimposed on the graph in custom proportion and values, but without

a phase shift, such that the time-bases are equal for deviation, satisfaction and the indicated residual load. Actual residual load values are plotted in Figure 5.1, though it is only important to point out that the residual load is defined negatively in the APM. A first thing to notice is the proportionality of the AVPP deviation and the residual load. Reflecting the residual load oscillation, the deviation curve follows the residual load curve very precisely, but of course it is capped at 0. This reflection generally applies to all AVPPs, the magnitude varies though. Note that there is a small phase shift in the deviation curve, preceding the residual load, due to the lookahead averaging, where the scheduling relies on residual load predictions which meet the actual residual load with a high accuracy, as seen in the graph. The explanation for the oscillation reflection per se is easily identified in the role of the residual load within the scheduling as a measure of scarcity. As stated in Section 4.4.2, an economy of scarcity is present if $D(t) > load_{res}(t)$, where the quantity of scarcity $s(t)$ can be assessed as the difference $D(t) - load_{res}(t)$. Since in the APM, there is always an economy of scarcity, i.e., $s(t) > 0 \forall t \Rightarrow load_{res}(t) < D(t) \forall t$, this definition can be relaxed, stating $s(t) \propto load_{res}(t)^{-1}$. Because the residual load in the APM ($load_{res}^{APM}(t)$) is defined negatively, it follows $load_{res}(t) = \left|load_{res}^{APM}(t)\right|$ and hence $s(t) \propto load_{res}^{APM(t)}$. Since in general the level of deviation is proportional to the level of scarcity, the deviation is also proportional to the APM residual load, as shown in Figure 5.5.
As elaborated in Section 4.4.1, a CPP's satisfaction is assessed through a reinforcement of satisfaction or dissatisfaction for the deviation laying inside or outside an epsilon-area respectively. The dashed black line in the plot indicates the epsilon threshold, which is $Max\left[\epsilon^{+}, |\epsilon^{-}|\right]$ in the case of this analysis, since the absolute deviation is used. It can easily be seen that when the deviation exceeds this threshold, the satisfaction decreases and vice-versa. Note, however, that firstly the regarded AVPP satisfaction is but only an average over all CPP satisfactions of an AVPP and secondly the lookahead aggregation may cause deviations. In a situation, where within $n$ lookahead steps, the satisfaction would be increased $n/2$ times and decreased $n/2$ times, the lookahead aggregation would annihilate the satisfaction change. In conclusion it can be stated that the satisfaction is quasi anti-proportional to the deviation and thus it is transitively anti-proportional to the APM residual load as shown in Figure 5.5.

Comparing the deviation-satisfaction curves of all AVPPs of $H_{flat}$ supports the above-described conclusions, while minor deviations can be explained through the lookahead aggregation effect. However the actual satisfaction curves differ significantly over individual AVPPs. Of course these differences are expected to be caused by individual legitimate claim valuations for the constituting CPPs, beside which structural reasons are assumed to influence the satisfaction distribution among the AVPPs. In order to explain these differences, the AVPPs are manually classified based on the characteristics of their satisfaction curves.

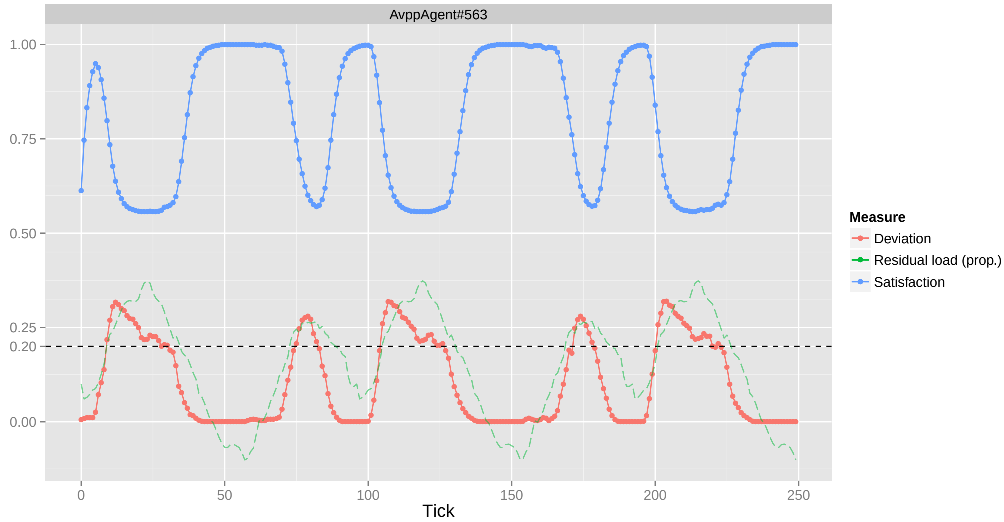



**Figure 5.5:** General residual load- and deviation-satisfaction-relation, shown in an exemplary AVPP of $H_{flat}$ in $E_{1,L}$ (run-aggregated). An AVPP's deviation is proportional to the residual load (qualitatively superimposed as green-dashed line), thus reflecting the residual load oscillation. The satisfaction is anti-proportional to the deviation threshold (black-dashed line) exceedance which therefore also reflects the oscillation.

Figure 5.6 shows the AVPPs' satisfaction histograms and the respective classification. The actual individual satisfaction curves and respective classifications are plotted in Figure 5.7.

A second classification criteria leading to the same classification is given as the CPP satisfaction – AVPP satisfaction relation. In the investigations so far, satisfaction referred to the AVPP satisfaction $\sigma^A$ (Eq. 4.12). However an AVPP also assesses a CPP satisfaction $\sigma^C$ (Eq. 4.5) about the outcome of its participation in its father's scheduling in the role of a CPP. An AVPP determines its demand as the sum of the demands of its constituting CPPs. As shown before, the satisfaction is anti-proportional to the scarcity level. A low CPP satisfaction $\sigma_a^C$ of an AVPP $a$ should result in a low AVPP satisfaction $\sigma_a^A$ and vice-versa, since the scarcity due to the small allocation for $a$ is distributed to its child CPPs which as a follow get high deviations and thus low satisfactions $\sigma_c^C$. These $\sigma_c^C$ are aggregated back to $a$ as AVPP satisfaction $\sigma_a^A$. Results of the experiments show however, that this does not hold for all AVPPs, as shown in Figure 5.7.

Four graduated classes are stipulated based on (1) $\sigma^A$ probability density properties and (2) on the $\sigma^A$–$\sigma^C$ relation as follows:

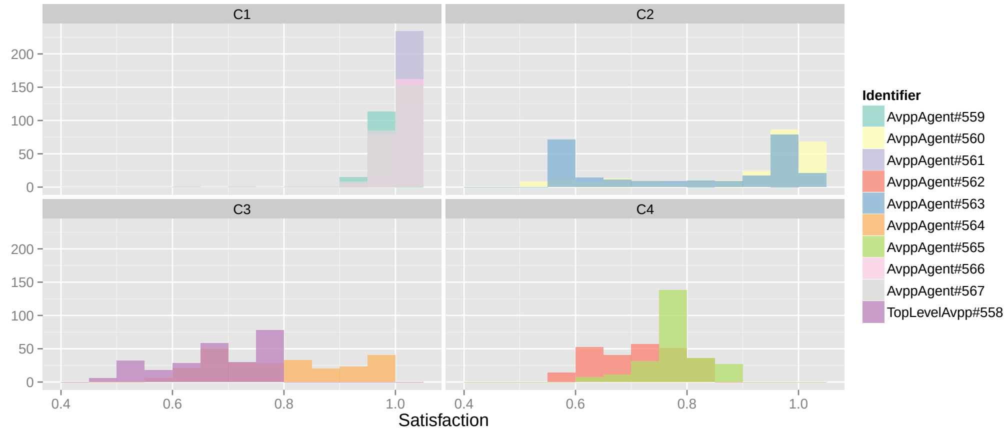



**Figure 5.6:** AVPP classification with respect to their satisfaction curve: AVPPs of $H_{flat}$ in $E_{1,L}$ are manually classified by characteristic satisfaction curve properties, comparatively illustrated as overlapping histograms in this plot, based on run-aggregation. Class $C1$ depicts sharp, left-skewed, high kurtosis satisfaction distributions, whereas $C2$ and $C3$ lead gradually over broad and flat distributions to $C4$ with moderate standard deviation and high symmetry.

| Class | AVPP sat. probability density | $\sigma^A$ | $\sigma^C$ |
|---|---|---|---|
| C1 | left-skewed, high kurtosis (significant peak), small standard deviation, mean ≈ 1 | high (≈1) | high (≈1) |
| C2 | middle kurtosis, large standard deviation | fluctuating ($\in [0.5; 1]$) | sharply fluctuating ($\in [0; 1]$) |
| C3 | middle kurtosis, large standard deviation | fluctuating ($\in [0.5; 1]$) | fluctuating ($\in [0; 1]$) |
| C4 | high symmetry (low skewness), moderate standard deviation | **high** (≈0.75) | **low** (≈0) |

Not all classes are clearly distinguishable for all individual AVPPs, especially C2 and C3 serve as a graduated transition from the highly contrasting classes C1 and C4. Randomly formed AVPPs have shown to be classifiable with the given classes as well such that this classification is assumed as generally valid and thus justifies this investigation approach.
Class C4 exhibits the $\sigma^A$–$\sigma^C$ relation contradiction: with low $\sigma^C_a$ of an AVPP $a$, and thus high resource scarcity within $a$, a low $\sigma^A_a$ is expected (and vice-versa, as described above and valid for C1). One explanation for this contradiction lays in the satisfaction averaging which hides the structural composition of

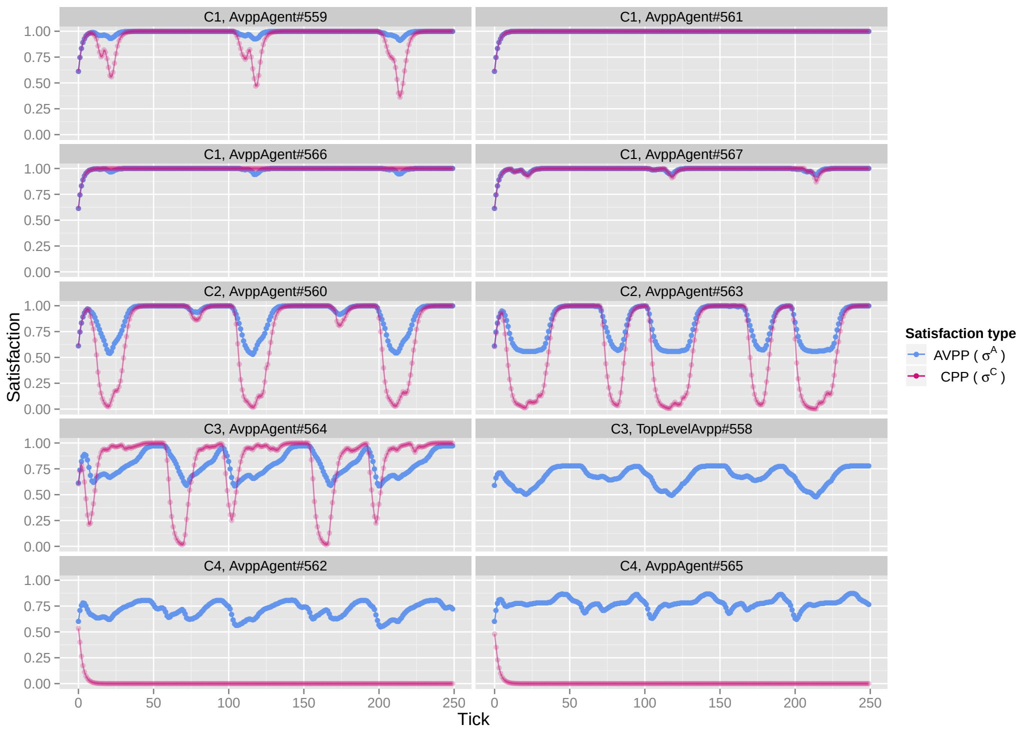



**Figure 5.7:** AVPP- and CPP-satisfaction relation as classification criterion of $H_{flat}$ in $E_{1,L}$ (run-aggregated). A low CPP satisfaction of an AVPP $a$ is expected to lead to low CPP satisfactions of $a$'s children and hence a low AVPP satisfaction of $a$, contrasting class C4 AVPPs.

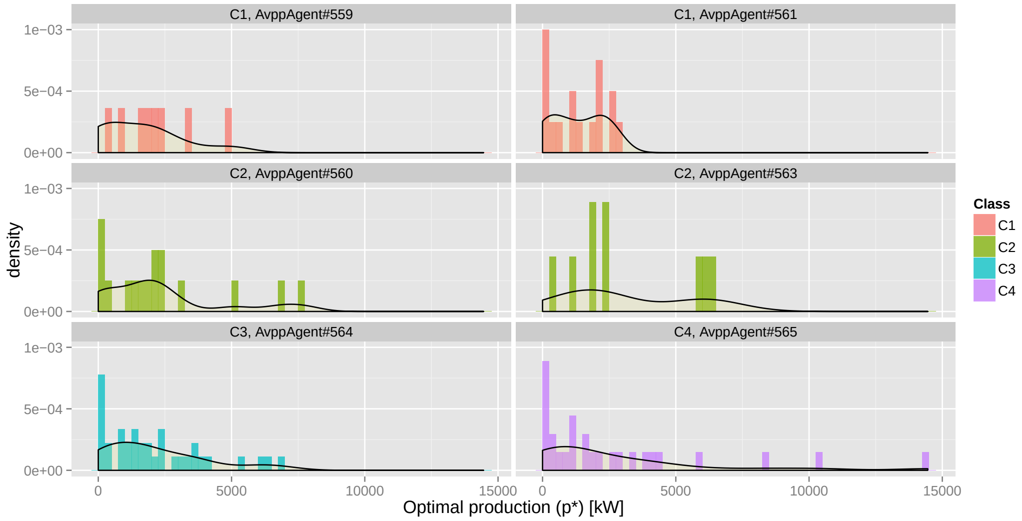



**Figure 5.8:** Optimal production probability densities and superimposed histogram of CPP compositions of exemplary AVPPs of all classes show a graduated transition from C1 with a short-tailed- to C4 with a long-tailed $p^*$-distribution, explaining the $\sigma^A$–$\sigma^C$ relation contradiction of C4. Run-aggregated data from $H_{flat}$ in $E_{1,L}$.

an AVPP, where the CPP distribution with respect to optimal production ($p^*$) may differ significantly. In the case of an AVPP $a$ with a high number of highly satisfied but small (w.r.t. $p^*$) CPPs and a small number of highly dissatisfied big CPPs (due to the present scarcity), the resulting $\sigma_a^A$ would be assessed as high, whereas $\sigma_a^C$ is low. An allocation in favour of small demands is incorporated through the canon of needs ($f_2$ in Section 4.4.3), thus it is highly probable for small CPPs to get their demand fulfilled and hence assess a high satisfaction, whereas big CPPs may get high deviations and low satisfactions. Figure 5.8 shows optimal production probability densities of CPP compositions of exemplary AVPPs of all classes. As shown, the $p^*$-distributions of C1 are short tailed, i.e., low standard deviation and small mean (e.g., $\mu = 1317$kW, $\sigma = 985$kW for *AvppAgent#561*), gradually changing up to C4 with long-tailed, i.e., high standard deviation and high mean (e.g., $\mu = 2740$kW, $\sigma = 3488$kW for *AvppAgent#565*), distributions. Note that range of $p^*$ of the CPPs used within the APM, whose models are obtained from real PPPs, covers 3 orders of magnitude, ranging from a minimum of 22kW of a hydro power plant to a maximum of 15,660kW, also for a hydro power plant, not regarding nuclear power plants, with $p^*$s of up to 1,410,000kW. In a C4 AVPP and a prevailing economy of scarcity, the potential dissatisfaction of a CPP is proportional to its optimal production, as is the hiding effect of the $\sigma^A$-averaging. It though is questionable whether the optimal production of a CPP should be considered in the father AVPP satisfaction which could be implemented by a $p_i^*$-weighed $\sigma_i^C$-sum average in the $\sigma^A$ calculation. This would reflect the power plant heterogeneity, being contrary to the equality paradigm though.

As a result of the preceding investigations, the following **AVPP formation criteria** aiming at high overall satisfaction and low satisfaction fluctuation can be stated:

**AVPP size trade-off on each layer:**
Due to the scarcity-satisfaction anti-proportionality, prevailing scarcity in an AVPP (due to small allocation) should be distributed to a 'high' number of children, such that an individual child perceives only a small fraction of the overall scarcity and thus has to suffer less deviations, which raises its and thus the AVPP's satisfaction. In the extreme example of the grand coalition (Figure 5.10a), the top-level AVPP $t$ is constituted of one child AVPP $a$, which itself is constituted of all 523 PPPs. In this situation, the resource scarcity, given as the total APM residual load is assigned to $t$ which fully delegates the scarcity to its only child $a$. The child $a$ itself spreads the scarcity to all CPPs. Also due to the above-described $p^*$ distribution implication, $\sigma_a^A \approx 1$, while $\sigma_a^C \approx 0$ and thus $\sigma_t^A \approx 0$.
However, too many constituents (e.g., Figure 5.10b) may lead to low satisfaction for some individual constituents. This increases the probability that these low satisfied constituents themselves trigger the reformation of their layer which could destabilise large parts of the hierarchy. Thus, a balanced AVPP size has to be identified and has to be considered by the AVPP formation mechanism.

**Balanced mix compositions:**
**1. With respect to optimal production:**
AVPPs should be constituted by heterogeneous CPPs w.r.t $p^*$, such that the CPP heterogeneity is spread equally among all AVPPs. Thus, the inter-AVPP similarity is to be maximised, while the intra-AVPP dissimilarity is to be maximised, which is performed by anti-clustering.

**2. With respect to other legitimate claim factors**:
Also regarding the factors valuated by other claims, like trust values, the CPP heterogeneity should be spread equally among all AVPPs. This can be achieved by performing anti-clustering on all other factors, valuated by claims.

Figure 5.9 shows the time-dependent **canon weights development** of the AVPPs of $H_{flat}$ in $E_{1,L}$. Since the actual weights are much more volatile, the graphs are smoothed to increased visual readability. The weighting is highly individual to the individual AVPP that executes the scheduling. This expresses their high degree of heterogeneity. A relation to the identified classes cannot be stated. Note that the CPP satisfactions $\sigma^C$ in Figure 5.7 are based on the respective outcomes in the top-level AVPP scheduling. Thus the canon weights of *TopLevelAvpp#558* are to be regarded in the explanation of individual allocations, deviations and satisfactions subsequently. Interestingly, the satisfaction canon ($f_{1b}$) is highly weighted in the top-level AVPP, hence dissatisfactions of the top-level AVPP's constituting AVPPs are expected to lead to positive valuations in terms of the satisfaction claim through the **satisfaction feedback loop**. Class C4 AVPPs with a very low $\sigma^C$ should highly benefit from that claim, however their $\sigma^C$ curve does not give empirical evidence for the effectiveness of the satisfaction feedback loop. The high weight of $f_{1b}$ is presumably caused by the self-interest voting component in the self-organising weight determination, which proves that this claims ranks AVPPs relatively high, keeping them selfishly voting for it. However other claims may counteract the favour of this claim such that the overall ranking is but influenced to a low degree from the satisfaction claim. The causal similar deviation canon ($f_{1a}$) is very lowly weighted in the top-level AVPP and thus does not support the deviation-/satisfaction feedback. Dedicated investigations on both claim weight determination and the impact of feedback effects may be part of future work.

## 5.4 Isolated evaluation of APM meso-level and micro-level structuration mechanism with LPG' scheduling

Before analysing the interference of the meso-level and micro-level adaptation mechanisms, the mechanisms are briefly evaluated qualitatively in isolation with focus on LPG' scheduling related properties, beginning with the inter-organisational self-organisation meso-level structuration mechanism which triggers layer actions in the introduction of new layers or dissolution of existing layers based on scheduling runtime exceedance and lower deviation, respectively. As elaborated in Section 2.3.2, in case of the introduction of a new layer, intermediary AVPPs which take over the constituents of their father AVPP, are introduced as new constituents of the father, using the APM AVPP formation mechanism. In the current APM version, a Particle Swarm Optimization (PSO) algorithm, instead of SPADA is used as formation algorithm. A layer is removed by assigning the constituents of an intermediary AVPP to its father AVPP. In the executing HiSPADA algorithm, scheduling runtime thresholds are modelled as constraints, observed within HiSPADA's control loop which triggers respective layer actions on constraint violation. Of course, this mechanism only depends on the underlying scheduling mechanism in terms of its runtime behaviour. Due to the assumed linear runtime behaviour of

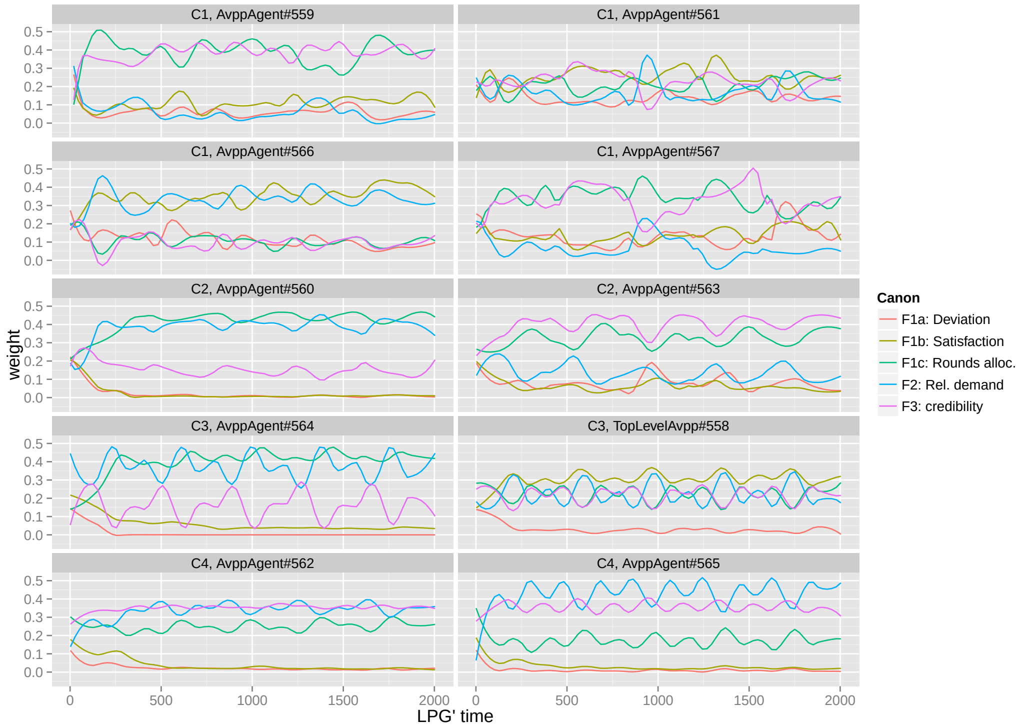
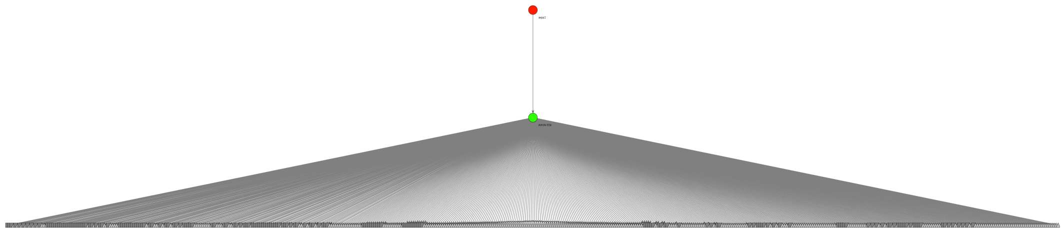


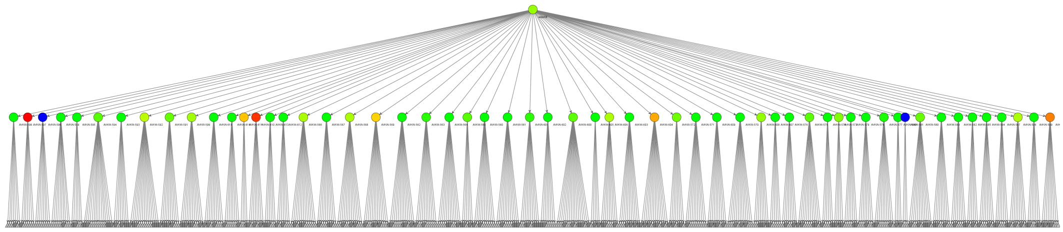

**Figure 5.9:** Smoothed canon weights curves in LPG' time base for the AVPPs of $H_{flat}$ in $E_{1,L}$ (run-aggregated), reflecting their heterogeneity. The AVPP classification is not applicable to the respective canon weights curves. In the average, the deviation and satisfaction equality canons are lowly weighted.

the LPG' scheduling, the scalability issue loses its significance. The size of an AVPP could be directly monitored and trigger layer actions according to violations of size thresholds.
The meso-level structuration mechanism behaviour was validated in a broad variety of parameter configurations, including variation of the initial hierarchy (pre-defined, random), the hierarchy type (flat, hierarchical) and distinctive combinations of `min. scheduling duration` and `max. scheduling duration` values. A pre-defined hierarchical structure $H_{hier}$ with hierarchy depth 5, as well as the pre-defined flat structure $H_{flat}$ is used, each using the standard parameter configuration (see Table 5.1). A stable hierarchy was formed in every run. However, the AVPP formation mechanism has to be able to produce suitable AVPP sizes, such that the minimum scheduling runtime threshold can be adhered at all. If the resulting minimum threshold is violated, a local *layer oscillation* occurs, that keeps removing and reintroducing the respective layer AVPP. This oscillation can be interpreted as an uninformed brute-force structuration approach, where solutions in form of structures are created and evaluated through the runtime constraints. A feasible solution would be depicted by not causing constraint violations. Thus the oscillation remains, until a feasible solution, i.e., a suitable AVPP size, was created 'by chance'. Figure 5.11 shows a stable repartitioning of a grand coalition initial structure, shown in Figure 5.10a, resulting within 14 ticks and 4 triggered layer actions in experiment $E_2$. The starting hierarchy depth of 2 was extended to 6, while $E_2$ defines `min. scheduling duration`=20ms and `max. scheduling duration`=150ms, resulting in maximum AVPP sizes of about 27 scheduling-participating constituents (CPPs and AVPPs including controllable constituents), using the previously-described constant time factor. Note that through the local adaptation, unbalanced trees are likely to result.

Through introspection of the satisfaction of its constituents the intra-organisational self-evaluating mechanism adapts an AVPP through dissolution if $\sigma^A$ falls below the `min. satisfaction threshold`. To take into account the promoted degree of self-organisation and thus the increased system dynamic in the LPG' scheduling, the dissolution is triggered by a time frame constraint which is violated if the satisfaction falls below the threshold `max. violations` times within `timeframe` ticks. The dissolution of an AVPP $a$ in the APM is technically implemented by assigning $a$'s constituents to $a$'s father $f$ followed by the reformation of $f$, using the PSO algorithm, as described above. The first experiment $E_3$ of $ES_3$ uses the standard parameter configuration (see Table 5.1) and a random flat initial hierarchy. Within $n = 10$ runs in $E_3$, all structures have shown to become *stable*, where stable is defined as no dissolution being triggered for at least one residual load cycle length, passing the global maximum scarcity level. Reformation events were rare though, with an average of approximately 7 events per run. To increase the rate of adaptations, `min.`



**(a)** The grand coalition structure results in high $\sigma_a^A$ for the intermediary AVPP $a$, but low $\sigma_t^A$ for the top-level AVPP $t$ since the scarcity fully impacts $a$ which perceives low $\sigma_a^C$ hence.



**(b)** The scarcity of the top-level AVPP $t$ is spread to 57 intermediary AVPPs on the second layer which thus perceive high satisfactions. However, some AVPPs suffer low satisfactions due to a total small number of constituting CPPs with unsuitable porperties.

**Figure 5.10:** Extreme examples of randomly determined hierarchies showing effects of suboptimal AVPP sizes. Circles represent AVPPs, squares represent CPPs and triangles represent SPPs. The colour grade indicates AVPP satisfactions (from red with $\sigma^A = 0$ to green $\sigma^A = 1$), while blue indicates absence of $\sigma^A$, e.g., when $|CPP| = 0$.

`satisfaction threshold` is set to 0.5 for all following experiments in $ES_3$. In $E_4$, using random flat initial structures, none of the $n = 4$ runs, became stable, showing a first characteristic of flat structures, with an average of 35 AVPPs: since it is only necessary that one of the AVPPs on the second hierarchy layer violates the satisfaction constraint and thus triggers a reformation of the whole layer, it is very unlikely to get stable structures, revealing the main issue of the current AVPP formation algorithm in use. It optimises formations with respect to trust-mix only, not regarding the identified structuration criteria aiming on high $\sigma^A$ as identified in the preceding section. Additionally, the PSO tends to create many small AVPPs which results in at least one AVPP of low satisfaction being produced with a high probability, as shown in Figure 5.10b, which would trigger the reformation of the whole layer. Larger AVPPs are more tolerate to dissatisfactions of individual AVPPs, as elaborated in the preceding section, and are thus preferable to promote endurance and stability. With a maximum scheduling time of 150ms, a well-balanced average AVPP size of 25

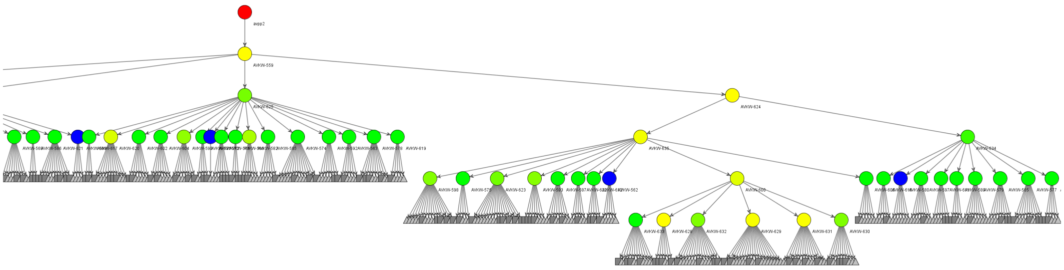
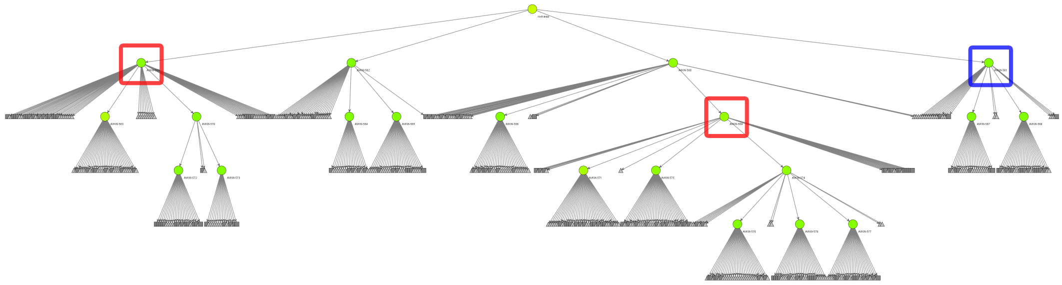


**Figure 5.11:** Excerpt of an exemplary meso-level structuration adaptation final stable result of $ES_2$ with an initial grand coalition hierarchy where 4 new layers were introduced within 14 ticks.

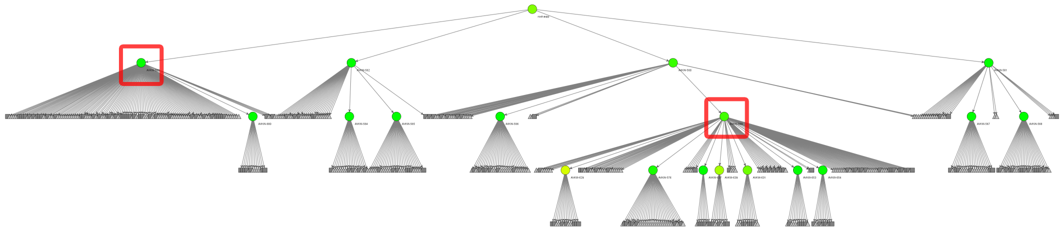
scheduling-participating constituents can be stipulated, resulting in about 18 AVPPs on the second layer.
Reformations within hierarchical AVPP structures, reflecting a SoS, are of high interest for this investigation and thus depict the focus of this analysis. In a total of 20 runs where the hierarchical initial structures of $n = 8$ runs of $E_5$ are determined randomly and the $n = 14$ runs of $E_6$ are pre-defined as $H_{hier}$, 6 randomly determined structures have shown to be stable from the beginning without any adaptation at all whereas one run each of $E_5$ and $E_6$ became stable after 20 reformations within the first 194 ticks. The latter case remained stable through the time frame constraint implementation, falling below the threshold $3(< 5)$ times within 10 ticks at high scarcity time periods. The conclusion of the flat structure analysis also applies to the hierarchical case: sparse subtrees, resulting from small AVPP sizes, have shown to be rather unstable through the high impact on individual AVPP satisfactions. Another observation is the relation stability impact to local scopes of reformations. In case of the stable $E_6$ structure, reformations were locally limited to two individual AVPPs, constituting subtrees of the overall structure tree, as shown in Figure 5.12. This pattern of repetitive locally bounded reformations can often be observed and tends to keep oscillating before converging to one following possible implications:

1. A stable formation is found, stopping the *reformation oscillation*, like in the described case. Since the current AVPP formation method does not aim at high satisfactions, the *reformation oscillation* can be interpreted as brute-force solution approach, like for the *layer oscillation*, where a solution would be evaluated through the satisfaction time frame constraint in this case.

2. Through unsuitable formations, dissatisfaction and thus dissolution decisions are propagated down in the hierarchy to possible individual AVPPs or subtrees.



**(a)** Initial $H_{hier}$ structure. The red squares indicate oscillating AVPP reformations. The blue-square indicated AVPP gets removed in $E_8$.



**(b)** A stable and well-satisfaction-balanced overall formation is reached after 194 ticks and 20 reformations, only in the marked AVPPs.

**Figure 5.12:** An initial hierarchical $H_{hier}$ structure of $E_6$ becoming stable after 20 reformation events within the first 194 ticks. Reformations are locally bounded to two AVPPs, marked with red squares in a), which ultimately produce stable formations after repetitively keeping restructuring.

3. Dissolution decisions are propagated up to AVPPs on higher hierarchy layers affecting possibly highly satisfied AVPPs.

Implication 1 has shown to be rather unlikely with the non-satisfaction-optimised formation, whereas up-propagations are more likely, while down-propagations are most likely due to their causal dependency for their children, whose scarcity is inherited by their father. The frequencies depend on the badness of the reformed composition and AVPP sizes. Especially sparse trees and small AVPPs are prone to assimilate the dissatisfaction due to the high relative influence of the reformed AVPP.
Dissolution up-propagations have often shown to destroy highly satisfied AVPPs super-structures through inclusion in the reformation process. In general, reformations on higher hierarchy levels have greater potential impact on the overall structure, due to the greater number of potentially affected substructures. In the positive case, an isolated low-satisfied subtree can increase its satisfaction through the reformation including ‘far’ upper-level AVPPs. This could be interpreted as escaping a local optimum through exploration. However, the negative effect of diminishing the satisfaction of whole subtrees could be

observed in many cases. Anyway, the decentralised system nature has to be borne in mind, when valuating these effects based on a global view. Thus overall well satisfaction-balanced structures, as a form of global optimum, should not be expected.

If the formation algorithm implements the identified criteria to promote overall satisfaction, the structural micro-level adaptation mechanism is expected to perform much better than the current implementation. In this case, a minimum satisfaction threshold of 0.5 is expected to still result in finding stable structures or at least decrease the reformation frequency. The time frame constraint implementation has shown to be an effective measure to meet the present higher level of self-organisation, however the implementation of a dynamic satisfaction threshold incorporating the present time-dependent global scarcity degree and thus expected level of dissatisfaction seems to be more adequate.

## 5.5 Interference of concurrently effective interleaving meso- and micro-structure adaptation mechanisms

In the last experiment set $ES_4$ the interference of concurrently effective meso- and micro-level structural adaptation mechanisms is investigated. Again, to increase the number of adaptation events, the following parameters override the standard parameter configuration: `min. satisfaction threshold`=0.5, `min. scheduling duration`=35ms. With the stricter minimum duration threshold and the standard `max. scheduling duration`=150ms, the effective allowed AVPP size approximately ranges between 10 to 30 scheduling-participating constituents.
The general adaptation event sequence in $E_7$ ($n$ = 10) with the pre-defined initial structure $H_{flat}$ of hierarchy depth 2 was observed as follows: firstly, additional layers are introduced for a small number of layer 2 AVPPs. Due to lower satisfaction deviations two AVPPs are dissolved secondly, triggering the reformation of the whole second layer, resulting in a similar state than shown in Figure 5.10b, except a small number of AVPPs are constituted of subtrees. Due to a high number of AVPPs on the second layer, a new layer is introduced. In following ticks, new hierarchy layers keep being introduced at a high frequency, opposing occasional layer removals and reformations. Reformatted AVPPs may violate runtime constraints and thus get dissolved in the next tick. The hierarchy depth gets increased to an average of 6. Because of the time frame constraint implementation of the micro-level structuration, reformations are triggered much less frequently since they are pre-empted by layer actions. This interferent behaviour is benevolent since the compliance of runtime constraints

is guaranteed, before the satisfaction constraint gets effective and thus before unsuitable structures would be possibly reformed. Rather stable structures result from intensive structural adaptation. Of 10 runs, with 500 ticks each, none has shown to ultimately become stable, however 7 runs showed only local *layer oscillations*, in which the opposing layer actions are repetitively introducing and deleting a layer about an AVPP.

$E_8$ ($n = 10$) uses the pre-defined initial structure $H_{hier}$ to investigate interferences in hierarchical structures, resulting in rather well-reproducible behaviour. In tick 4, the hierarchy level of AVPP $a$, indicated with a blue square in Figure 5.12a, gets removed, resulting in $a$'s constituents being moved to the top-level AVPP. In most runs (9 of 10), only the red-square marked AVPPs in the figure, kept layer-oscillating afterwards. In 2 runs, both marked AVPPs kept oscillating, in 5 runs only one of them kept oscillating, whereas in 2 runs, the structure got ultimately stable after about 220 ticks in which also reformations got triggered.
As in the experiment sets before, a randomly determined hierarchical structure promotes the revelation of interference characteristics and is thus used in $E_9$ ($n = 20$). Characteristics and phenomena identified before are confirmed through observations in this experiment. All runs showed common similar behavioural elements, already described above: in the beginning, reformations and introduction and removal of layers are triggered with high frequencies, correlated to the initial overall suitability degree of the structure. Through the implementation of the AVPP dissolution as a time frame constraint, such adaptations are detained through layer actions being triggered still within the given time frame. Sparse subtrees show to be more unstable. The high number of adaptations leads to more stable overall states, with mixed stable and still oscillating subtrees. The frequency of adaptation events decreases as more stable structures evolve. The majority of adaptations are effective on AVPPs on the second and third layer in the beginning, however, subtrees on higher hierarchy layers tend to get reduced in diameter, such that the average initial hierarchy depth of 7 gets reduced to 3-4 over time. This can be interpreted as top-down, destructive structuration, converse to the behaviour with flat initial structures, where a more stable state evolves through constructively constitute a hierarchical structure. The removal of layers on lower hierarchy layers tend to stabilise the layers above, since their constituents are assigned to their fathers, thus causing the $\sigma^A$ stability effect of high number of constituents as described above. Also the potential mixing effect, described as explorative behaviour before, is hence increased. Since the PSO tends to create small AVPP sizes, the stability of the structures in the investigation of adaptation through reformation only has shown to be limited. In this investigation though, the higher minimum scheduling time threshold ensures larger AVPP sizes, overall promoting the likelihood of more stable structures, which is approved through the high number

of ultimate stable structures in $E_6$: 13 runs developed stable states, 4 runs showed only local oscillations (reformation or layer actions) on 1 or 2 AVPPs, whereas only 3 runs kept adapting in a large scale throughout the 500 ticks. An exemplary run showing local oscillations is shown in Figure 5.13.

In conclusion it can be stated that the interferences of the meso- and micro-level structure adaptation mechanisms are supportive to collectively form more stable structures. This at least applies in the case of the AVPP dissolution in the micro-level adaptation being triggered through the violation of a time frame constraint. If both adaptations would get triggered concurrently on a common element on a regular basis, the interferences may consist in abrogating each other's adaptations in the short time, presumably resulting in overall less stable structures or at least increased adaptation and stabilisation durations. If the formation mechanism implements the satisfaction-promoting criteria, much better results in terms of diminished adaptation event frequencies and oscillations are expected.

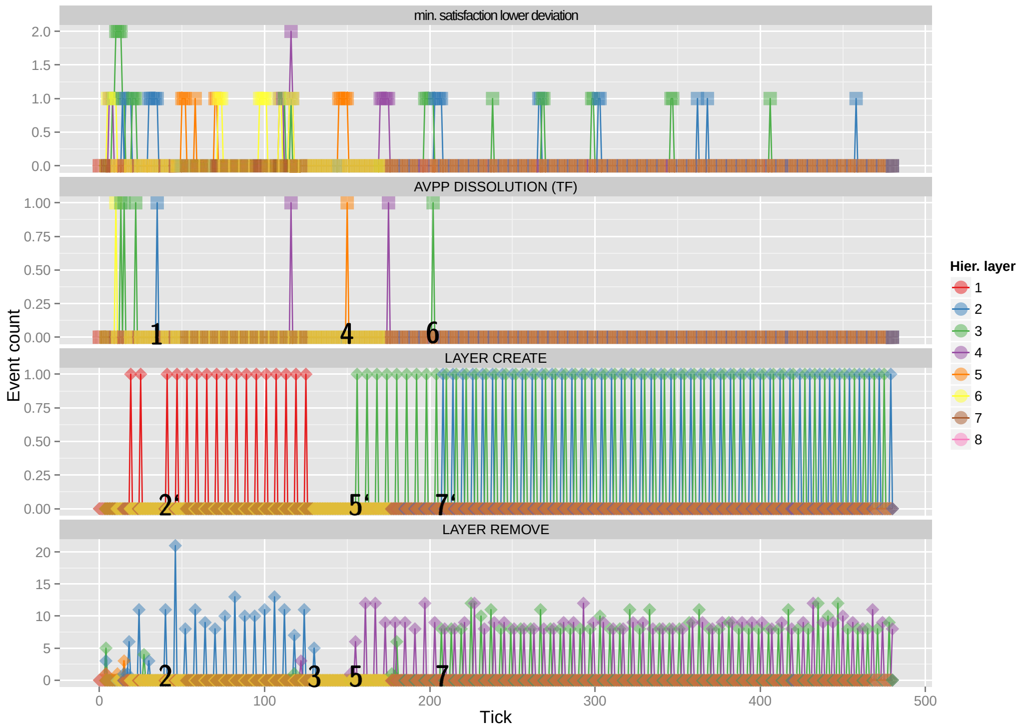



**Figure 5.13:** Meso- and micro-level adaptation events in an exemplary run of $E_9$ showing local oscillations. The first graph shows individual lower deviations of the minimum satisfaction threshold, whereas the second graph shows micro-level adaptation events triggered through violation of the minimum satisfaction time frame constraint. Graph three and four show meso-level adaptation events of layer creations and removals respectively. After adaptations in the first ticks, an AVPP on the second layer gets dissolved at tick 35 (1), causing the reformation of that layer, which as a result violates the minimum scheduling time constraint, triggering the removal of that layer at tick 40 (2), which itself triggers a local layer oscillation of introduction and removal (2') of that layer until a valid size is found at tick 130 through the removal of that layer (3). AVPP dissolutions at tick 150 (4) and 202 (6) trigger analogous high-frequency local layer oscillations (5, 7) which remain to the end of the run at tick 500. In parallel, individual AVPPs occasionally lower deviate the satisfaction threshold, not violating the satisfaction time frame constraint though.

# Chapter 6

# Conclusion & Outlook

In this Thesis, the distribution component of the case study APM system in form of the autonomous scheduling process within an AVPP as part of a hierarchical SoS is replaced by a self-organising legitimate claim resource allocation system, based on the LPG' which incorporates fair resource allocations based on Rescher's canons of legitimate justice and Ostrom's principles for enduring CPR allocation institutions. Conceptual differences are identified mainly in the level of abstraction, which is abstract in case of the LPG' and rather technical through the APM's cyber-physical system nature. Its mission-criticality justifies the limitation of agent autonomy in terms of intentional rule violation and adherence of physical hard constraints on the one hand, compensated on the other hand through the sacrification of the optimality in the CSOP-based APM scheduling and the incorporation of Ostrom's principles like collective-choice arrangements in the self-organised claim-weight determination for instance, overall promoting both agent-autonomy and degree of self-organisation and complement the APM's self-organising meso- and micro-level structuration adaptation mechanisms. Subsumingly stipulated requirements for the solution approach given as the adoption of Ostrom's principles, the adherence of hard constraints, establishment and promotion of fair CPR scheduling through the implementation of Rescher's canon of distributive justice in form of legitimate claims as well as a sophisticated satisfaction metric, living up with the economical context of the APM, are shown to be satisfied in the realisation: the APM scheduling is performed by an allocation system constituting an electronic institution incorporating Ostrom's and Rescher's principles and paradigms. Allocations are determined through hard-constraint adhering allocators, selected based on the prevailing state of the environment regarding resource scarcity. The satisfaction about its outcomes are assessed by participating power plants based on asymmetrically modelled deviation and satisfaction metrics, considering individual and model-inherited economic minutiae of respective power plants. AVPPs evaluate their fitness for purpose through introspection of the satisfaction of their constituting power plants, triggering their dissolution and

reformation if deemed unfit for purpose.
Elaborated empirical analyses prove the superiority of the LPG'-based scheduling compared to its CSOP pendant regarding overall satisfaction and fairness. Furthermore the AVPP deviation-satisfaction correlation is investigated resulting in an AVPP classification which also is applicable for the explanation of observed discrepancies of AVPP- and CPP-satisfaction. Finally, suitable AVPP formation criteria are derived from the classification, which shows to be of structural origin and subsumed as AVPP size trade-off and balanced mix composition. A short analysis of the legitimate claim weights development shows no strong evidence of the conceptual satisfaction and deviation claim feedback loop. The analysis of isolated structural adaptation mechanisms exhibits the main issue of unsuitable AVPPs formation, their functional correctness can be showed however. Oscillations of both meso- and micro-level adaptations are observed in isolated and concurrent adaptations as the main interference pattern due to interleaved adaptation. Interferences of the adaptation mechanisms are classified as benevolent to collectively form more stable structures.

Further work on the conceptual side could include the incorporation of the concept of *social capital* in the APM's power distribution as part of the electronic institution: power plants could accrue social capital through stepping in to compensate unintentional errors of other power plants, which could be positively valuated in a claim or be reciprocally rewarded by the malfunctioning power plants themselves in other situations. The claim mechanism could also be used to favour certain power plant types. Furthermore, the AVPP satisfaction could be extended by the inclusion of both other aggregated CPP properties like trust-mix or other aggregation data as well as of AVPP meso-level scope properties like scheduling violations. This could lead to a multi-criteria AVPP dissolution mechanism, possibly also complemented by user-defined criteria like power plant type composition, which would raise potential conflictual bottom-up and top-down dissolution decisions, e.g., when the constituting power plants are highly satisfied, but the AVPP itself evaluates its power plant type composition as unfit for purpose. In such cases, a conflict resolution mechanism is needed, which could implement a collective-choice arrangement as described by Ostrom. As shown in the evaluation, the minimum satisfaction threshold in the AVPP dissolution mechanism could be improved by being dynamically adjusted based on the current system state in terms of scarcity level, such that the system is more tolerant in times of high present scarcity. Alternatively, the present scarcity level could be incorporated in the CPP's satisfaction assessment. In the analytical domain, a dedicated analysis on claim-weights and the claim-feedback loop could be performed, further investigating the interference through back-coupling.

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