The logic of information and processes in system-of-systems applications

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***Abstract*—Logic and many-valuedness as proposed in this paper enables to describe underlying logical structures of information as represented within industrial processes, and as part of their respective markets. We underlines the importance of introducing classification structures in order to enable management of information granularity within and across subsystems in aa system-of-systems. The *logic of information and process* is a main contribution of this paper, and our illumination of a system-of-systems is drawn within the field of energy. In our process view we look closer into the power market with all its stakeholders, and e.g. as related to renewable energy. Supply, demand and pricing models are shown to become subjected to logical considerations. In our approach we show how information and their structures are integrated into processes and their structures. Information structures build upon our many-valued logic modelling, and for process modelling we adopt the BPMN (Business Process Modeling Notation) paradigm.**

***Index Terms*—Business Process Modeling Notation, energy, lative logic.**

I. INTRODUCTION

In system-of-systems (SoS) applications, engineers typically see *information* as residing in products and subsystems taxonomies, and even specifically as emerging from measuring devices. However, in the case of energy, it is part of a market with a variety of stakeholders. Public opinion and governance, as well as related rules and regulations, affect this market in one way or another. Energy can roughly be seen as produced, transmitted, distributed and consumed, where the sources of energy ar renewable or non-renewable. The system as a whole enables to identify risk and opportunity, and fine-granular information structures enable accuracy and completeness of information models.

Uncertainty is often viewed statistically as a phenomenon of variance. Therefore, uncertainty is more seldom modelled by logical many-valuedness, which adds complexity to this information representation. Furthermore, uncertainty as part of many-valued logic in systems-of-systems applications, is required when observing conditions as a basis for providing efficient and effective decision-making e.g. as related to service and maintenance.

In this paper we will show how uncertainty resides in various elements in logic, thus constituting an overall many-valaued logic for systems-of-systems.

II. THE LOGIC OF PROCESSES

Categorial frameworks provide suitable formalism for logical structures, with term monads [9] and sentence functors [10] playing fundamental roles in these respects.

When departing from bivalence to many-valuedness, and in particular for the set of valuations, *quantales* [16], [17], as algebraic structures, have been shown to provide suitable structures in particular given their capability to embrace non-commutativity.

A. The role of classifications for information and processes

In [11], [13] we showed how quantales providing valuation in disorder (ICD) and functioning (ICF) is arranges tensorially in a setting for disorder and functioning within health care. For modelling and many-valued and quantale based valuation of faults ($EnFa$) and functioning ($EnFu$) in the energy SoS and its design structures, we have a similar tensor

$$EnFu = EnFa \otimes EnFa,$$

where $EnFa$ typically is a three-valued non-commutative quantale, and the tensored $EnFu$ becomes a six-point non-commutative quantale. For detail, see [11]. This tensor clearly reflects the situation that a valuation of a multiple fault system-of-systems fault-fault interaction of $EnFa$ encoding corresponds to the way valuation of $EnFu$ based functioning is done with respect to $EnFu$ encoding. More generally, encoding in this manner is further integrated in modelling standards like `UML`, `SysML` and `BPMN` [7].

This paper builds upon and further extends a *logic of BPMN* approach adopted in [12] for modelling process generally in crisis management, and emergency care in particular. Engineering, procurement and construction (EPC) as related to plant project management for fossil fuel engine based power plants was developed in [15], [18].

Within the overall energy SoS, there are several important subsystem to be identified with respect to intensity of logic. One is the smart grid and smart transmission where we build upon smart grids as introduced in [1]. The descriptions in [1] are quite general and informal, but do cover the entire spectrum of the electrical system, from transmission to distribution and delivery. Our process model framework enables to embraces a BPMN subview also of smart grids.

B. Lative logic

The notion of logic as a structure embraces signatures and constructed terms and sentences *latively* constructed [6], [7] as based on these terms. Similarly, sentence and conglomerates of sentences are fundamental for entailments, models and satisfactions, in turn latively to become part of axioms, theories and proof calculi. This lativity is always produced and maintained by functors and monads, and as acting over underlying categories in form of monoidal categories. Category theory is thus a suitable metalanguage for logic, in particular when applications and typing of information must be considered.

Uncertainty may reside in generalized powerset functors, and may be internalized in underlying categories. In both cases, suitable algebras must motor this uncertainty representation, and quantales are very suitable in this context [11].

Substitutions as morphisms in Kleisli categories of term monads, carry data and information within and across subsystems, where each subsystem is seen as a logical theory Thereby we have the distinction between expression and statement within the SoS. Expression is a term produced by a term functor over a signature, and over an underlying category. We have separate and specific signatures within all subsystems. A statement is a sentence produced by a sentence functor [10].

Quantales are well suited for describing multivalence in many-valued logic, when valuation of uncertain information is subjected to various algebraic operations. This provides a unique situation where proper logical and mathematical foundation will meet the requirement of richness needed in real-world applications. Non-commutativity in these operations is a typically important consideration from application point of view. It represents a causality which intuitively resides between commutative conjunction and non-commutative logical implication.

In the following we briefly introduce notation and constructions needed in our descriptions related to our energy SoS signatures and terms. The many-sorted term monad $\mathbf{T}_\Sigma$ over $\mathtt{Set}_S$, the many-sorted category of sets and functions, where $\Sigma = (S, \Omega)$ is a signature, can briefly be described as follows. For a sort (i.e. type) $\mathtt{s} \in S$, we have sort specific functors $\mathsf{T}_{\Sigma,\mathtt{s}} : \mathtt{Set}_S \to \mathtt{Set}$, so that

$$\mathsf{T}_\Sigma(X_\mathtt{s})_{\mathtt{s}\in S} = (\mathsf{T}_{\Sigma,\mathtt{s}}(X_\mathtt{s})_{\mathtt{s}\in S})_{\mathtt{s}\in S}.$$

The important recursive step in the term construction is

$$\mathsf{T}^{\iota}_{\Sigma,\mathtt{s}}(X_\mathtt{s})_{\mathtt{s}\in S} =$$
$$\coprod_{\mathtt{s}_1,\ldots,\mathtt{s}_m} (\Omega^{\mathtt{s}_1\times\cdots\times\mathtt{s}_m\to\mathtt{s}})_{\mathtt{Set}_S} \times \mathsf{arg}^{\mathtt{s}_1\times\cdots\times\mathtt{s}_m} \circ \bigcup_{\kappa<\iota} \mathsf{T}^{\kappa}_{\Sigma}(X_\mathtt{s})_{\mathtt{s}\in S}$$

and then with

$$\mathsf{T}^{\iota}_{\Sigma}(X_\mathtt{s})_{\mathtt{s}\in S} = (\mathsf{T}^{\iota}_{\Sigma,\mathtt{s}}(X_\mathtt{s})_{\mathtt{s}\in S})_{\mathtt{s}\in S},$$

we finally arrive at the term functor

$$\mathsf{T}_\Sigma = \bigcup_{\iota<\bar{k}} \mathsf{T}^{\iota}_{\Sigma}.$$

The purely categorical construction of the corresponding term monad can be seen in [9].

C. Process modelling

For process modelling, BPMN diagrams build syntactically upon four basic categories of elements, namely Flow Objects, Connecting Objects, Artifacts and Lanes. Flow Objects, represented by Events, Activities and Gateways, define the behaviour of processes. Start and End are typical Event elements. Task and Sub-Process are the most common Activities. There are three Connecting Objects, namely Sequence Flow, Message Flow and Association. Gateways, as Event elements, handle branching, forking, merging, and joining of paths.

A Data Object is an Artifact, and having no effect on Sequence Flow or Message Flow. Data Objects are indeed seen to "represent" data, even if BPMN does not at all specify these representation formats or rules for such representations. However, Data Objects are expected to *provide information about what activities require to be performed and/or what they produce* [2]. Information produced is in our sense the result of a reduction or inference, with related substitutions.

Notion like '*service* provision' or 'failure *report*' in terms of their content and data formats is often well understood but this is not the case when considering provision and reports as structured *documents*, as a whole. To better understand the documents as a whole we must consider in detail the notions of documents, document structures, and document templates. In the categorical framework outlined above we can indeed identify *a document over a signature* Σ with the notion of a ground term over Σ, i.e., a term containing no variables. In this interpretation a *document template over a signature* Σ then is a non-ground Σ-term over some set of variables X. That is, $\mathsf{T}_\Sigma(X) \setminus \mathsf{T}_\Sigma(\varnothing)$ is the set of all document templates. We may underline here that the report structure really *is* the signature Σ?

Our suggestion for information semantics [5] is then that BPMN's `Data Object` coincides with document and, by extension, is a ground term. For documentations and document refinements, this means in reality that we call a document draft a 'document template' all the way until it has been matured to become the "finished" document, where all variables have been instantiated with relevant information (ground terms). Similarly, 'token' coincides with variable substitution. From this view of BPMN information semantics, we are able to extract at any point in the data flow a valid variable substitution that precisely represents an information snapshot of the process at that particular point. An activity in the BPMN sense can then be viewed as a composition of variable substitutions with the initial token or variable substitution being the Kleisli category identity morphism $\eta : X \to \mathsf{T}_\Sigma X$.

In order to provide examples, let us briefly outline how the underlying signatures as 'owned' and recognized by respective disciplines might look like. In our example we may start with the signatures,

$$\Sigma_{transmission} = (S_{transmission}, \Omega_{transmission})$$
$$\Sigma_{distribution} = (S_{distribution}, \Omega_{distribution}),$$

respectively, for the subsystems of energy transmission and distribution stakeholders.

We may aim at providing failure reports as terms t being of sort $\mathtt{s}_{FailureReport} \in S_{distribution}$. This may also be denoted by $t :: \mathtt{s}_{FailureReport}$. This term t is then seen as produced by a number of operators, manipulating and attaching terms in form of various 'subdocuments', like a specific cable failure report to be integrated with the overall failure report. Assume then we have the cable report, as a term being $u :: \mathtt{s}_{CableReport}$, with $\mathtt{s}_{CableReport} \in S_{transmission}$. The term u is then typically delivered by operations as a response to a referral, $\mathtt{v} :: \mathtt{s}_{ReferralToTransmissionMaintenanceReport}$, with $\mathtt{s}_{ReferralToTransmissionMaintenanceReport} \in S_{transmission}$, from a first responder onsite where the failure has been identified.

The refinement of failure and maintenance reports are assumed to include detailed energy engineering knowledge as typically appearing in diagnostic and maintenance guidelines of various kind and with different level of detail.

Report production, enhancement and enrichment is then enabled, e.g., by operators like $\mathtt{RefineReport}_{\mathtt{s}} : \mathtt{s} \to \mathtt{s}$, where in the case of $\mathtt{s} \in S_{transmission}$ it is report production authored by maintenance and service.

Suppose now we are given classifications for failures, `ClEnFa`, and functioning, `ClEnFu`. Failure taxonomies typically as fault trees usually exist, whereas functioning classification are rare.

We would arrange these within an over BPMN *data object signature*, so that we have $\mathtt{ClEnFa}, \mathtt{ClEnFu} \in S_{DataObjectSorts}$, e.g., with constant $\mathtt{c} :\to \mathtt{ClEnFa}$ representing a particular specific fault recognized in the fault tree.

As an example, consider a failure report. We may have as a template of such a report a non-ground term

$$\mathtt{DiagnosisAndReassessment}(\ldots, x_{\mathtt{s}_{CableReport}}, \ldots)$$

so that a particular activity performed by the first responder (having a unique personal ID, say 4321) will then give rise to a many-sorted substitution σ such that

$$\sigma_{\mathtt{s}}(x) = \begin{cases} t & \text{if } \mathtt{s} = \mathtt{CableReport} \\ x & \text{otherwise} \end{cases}$$

where

$$\begin{aligned} t = \mathtt{CableReport}(&\mathtt{frId}(4321), \\ &\mathtt{Cables...} \\ &\mathtt{Conductors...} \\ &\mathtt{DeadEndTower...} \\ &\ldots). \end{aligned}$$

The term resulting from this substitution – which may still be a template, but nevertheless is closer to a document – will be

$$\mathtt{FailureReport}(\ldots, \mathtt{CableReport}(\ldots), \ldots)$$

and we can view it in the following, alternative, form

```
|----- Failure Report
|
| ... transmission line location ...
|
|    |----- Cable Report
|    | frID = 4321
|    | Cables ...
|    | Conductors ...
|    | Dead-end tower ...
|    |-----
| ...
|-----
```

Our view of BPMN information semantics in this paper differ from [12] where Data Objects were taken to be variable substitutions.

Uncertainty can be modelled using composition of many-valued power monads with the term monad, i.e., $\mathbf{Q} \bullet \mathbf{T}$, where $\mathbf{T}$ is the term monad and $\mathbf{Q}$ as the many-valued powerset monad based on an underlying quantale Q. The structure of substitutions,

$$(\mathrm{Hom}(X, \mathsf{QT}X), +, \cdot, ^*, 0, 1),$$

i.e., the set of morphisms in the Kleisli category $\mathtt{Set}_{\mathbf{Q}\bullet\mathbf{T}}$, is a Kleene algebra. See [12] for detail.

For substitutions $\sigma_1, \sigma_2 \in \mathrm{Hom}(X, \mathsf{LT}X)$, we have

$$\sigma_1 + \sigma_2 = \sigma_1 \vee \sigma_2,$$

and

$$\sigma_1 \cdot \sigma_2 = \sigma_1 \diamond \sigma_2$$

where $\sigma_1 \diamond \sigma_2 = \mu_X^{\mathbf{Q}\bullet\mathbf{T}} \circ \mathsf{QT}\sigma_2 \circ \sigma_1$ is the composition of morphisms in the corresponding Kleisli category of $\mathbf{Q} \bullet \mathbf{T}$.

A "partial algebra of documents" can now be provided as follows. Let $\mathtt{t}_{CableReport} :: \mathtt{s}_{CableReport}$ be a template, or "document in progress", as part of an overall term

$$(\mathtt{t}_{\mathtt{s}}^{ScopeOfReport})_{\mathtt{s} \in S_{DataObjectSorts}}$$

in

$$\mathsf{T}_{\Sigma_{DataObjectSignature}}(X_{\mathtt{s}})_{\mathtt{s} \in S_{DataObjectSorts}},$$

with substitutions σ_i, $i = 1, 2$. Then

$$\mu \circ \mathsf{T}(\sigma_1 + \sigma_2)((\mathtt{t}_{\mathtt{s}}^{ScopeOfReport})_{\mathtt{s}})$$

is a concatenation or composition of information along a path of maintenance tasks, of $\mu \circ \mathsf{T}(\sigma_1)((\mathtt{t}_{\mathtt{s}}^{ScopeOfReport})_{\mathtt{s}})$ and $\mu \circ \mathsf{T}(\sigma_2)((\mathtt{t}_{\mathtt{s}}^{ScopeOfReport})_{\mathtt{s}})$, whereas

$$\mu \circ \mathsf{T}(\sigma_1 \cdot \sigma_2)((\mathtt{t}_{\mathtt{s}}^{ScopeOfReport})_{\mathtt{s}})$$

is a corresponding 'sharpening the uncertainties', or enhancing truth values residing in that report.

III. ENERGY

Energy sources in our nature are often subdivided into renewable and non-renewable sources. Opportunistic and coarsest-granular politics may say only “we need more focus on renewable”. However true it may be, it hides detail and granularity of the underlying information structure of pros and cons. Awareness raising among the public enables finer-granular opinion making, which in turn enables the consumer to understand how to affect supply and demand.

Renewable sources include geothermal, hydro, water and wind. Non-renewable source. include fossil and nuclear fuel.

Concerning renewable energy, who owns sunlight, flow of water, underground heat or windy air? We all do. We can all exploit it, under certain rules and regulations, given opinions and policies. And we all do, sometimes even so that rules and regulations are updated, and more opinion and policy is created.

A. The logic and fungibility of the Energy Market

In the following we will show some snapshots from an overall BPMN view of *The Lative Logic and Fungibility of ENERGY*, using the following stakeholders in respective BPMN Lanes:

- Power SOURCE
- Central or Federal GOVERNMENT
- National and Regional AUTHORITY
- Local GOVERNMENT
- Power Model
- Power MARKET
- Power Plant EPC
- Power Plant MAINTENANCE
- Power Plant EPC
- Power GENERATION
- Power TRANSMISSION
- Power DISTRIBUTION
- Industrial CONSUMER
- Public CONSUMER
- Household CONSUMER

Opinion, policy making and governance, in dialogue and interaction over time, are important parts of the energy market SoS (Figure 1).

B. Energy to current and back to energy

Force and energy residing in flow of water and wind create rotation so that attached generators can convert mechanical energy to electrical energy. Electric charge is a fundamental conserved property as appearing in electromagnetic interaction.

This is the ideal electrophysical situation. In practice, current is lost in transmission, and for a wide variety of reasons. Improved efficiency and reliability in transmission becomes important. In ideal situations, the power P, in watts, is equal to the current I, in amps, times the voltage V, in volts, i.e., $P = I \times V$. Currency loss is modelled using a power factor pf, so that in a realistic situation we have

$$P = pf \times I \times V.$$

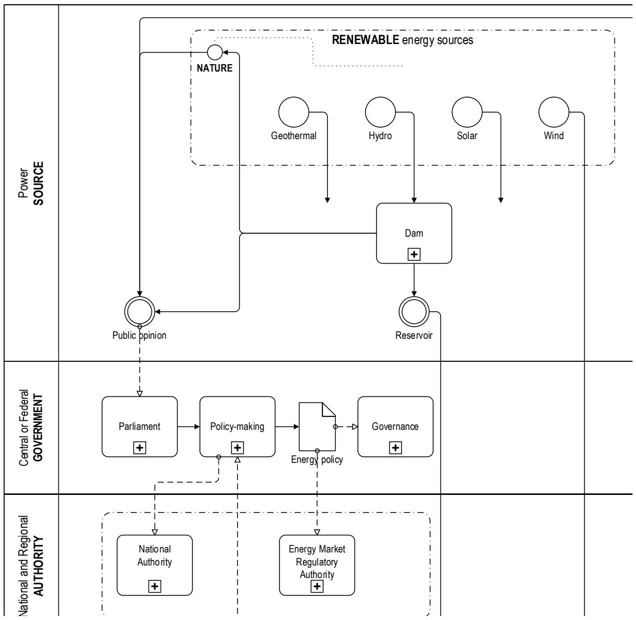

Fig. 1. Policy making and public opinion in dialogue.

In practice, the calculation and estimation of pf is non-trivial. and the value itself can seldom point at where and why currency is lost. A number of techniques help to improve the power factor. Measuring the power factor, however, is usually an average condition, which means it does not reveal if a power factor decrease is a widespread or a localized problem. Furthermore, electric energy distribution using overhead and underground power lines makes the power factor differently transparent. Overhead power lines are more economical, but also more susceptible to damage. Repairing physical damage is very expensive. From logic point of view, pf is still a numerical value, but not a constant. It is a many-valued logical term (expression) $\mathtt{pf}(t_1, \ldots, t_n)$, where its value in turn depends on subterms $t_1, \ldots, t_n$, so that outcome power is logically computed as

$$P = \mathtt{pf}(t_1, \ldots, t_n) \otimes (I \times V).$$

Obviously, this is still an informal expression as it mixes logical and numerical computation, but it clearly enriches the value to become an valuated expression, where the reason e.g. for power factor los can be contributed to observations integrated into the terms $t_1, \ldots, t_n$, some of which may be bivalent and instanteous, while others are dynamic and multivalent.

Tangible and intangible impacts of current loss altogether makes it difficult for the electric utility industry e.g. to justify the placing of overhead power lines underground. Power factor considerations differ and need to be considered also for underground cables [14]. This is a simple yet very concrete example where investments in transmission efficiency and safety has a direct effect on needs to adjust energy transmission pricing.

C. Failure and recovery

Failure described only by name, without structured information about the failure, has the consequence that time, to and between failures [3], is the only value pertinent to a failure. In reliability engineering, failure rate is seen simply as the frequency with which an (sub)system or component fails. This means counting *how many* failures per unit of time, rather than in addition explaining *how* it occurs and *what* precisely it pertains. Using only time as the only pertinent characteristic of a failure leads to risk analysis being mostly based on probability of occurrence. Intrinsic reasons of failure are hidden behind observation of failure frequency.

Our approach leans on failure and how it is valuated as described at a level of granularity, which is sufficient for providing required solutions e.g. in service and maintenance. Granularity of that description resides in the granularity of the underlying signature for the logic of the system. A signature with one sort for 'failure', and constant operators simply as names for failures, indeed means time is the only value pertinent related to failure.

Many-valuedness adds further granularity to valuation of failure and recovery. In some cases, a failure can be instanteous, but in general, a failure is a progression from normal to failed, passing through a number of stages which are either reversible or from which a process can recover before reaching a final failure state. Recovery is then a *dual* progression, similarly passing from failure through a number of stages to full recovery, and from there back to normal operation.

A failure may also be instantaneous and total, but local and residing in a certain subsystem, so that the failure status on the system-of-systems level is less critical. Recovery as described on local level is therefore also not to be identified with recovery taking place on more global level.

Further, a production process in transition to failure may sometimes lose only level of quality. but may maintain level of quantity, so that recovery makes quality return to normal level, whereas quantity levels remain unchanged.

Failure is a special for of *crisis*, where the description of a crisis is much more complicated. Roughly speaking, a failure can be more easily valuated, whereas a crisis is more of a process. A valuation like "mean time to or between crisis" obviously makes less sense, if any sense at all. *Recovery* from failure and *mitigation* from crisis is therefore not to be confused.

Which values and value structures then are most pertinent to failure and recovery in a specific system? A system build upon its underlying signature, so value expressions build upon sorts and operators in that signature. The *total effect* of a failure is then also a more complicated matter where *generalized integrals* need to be developed. Syntactic derivates based on underlying signatures was developed in [8], and can potentially be used to develop corresponding generalized integrals for the purpose of valuation and total effect of failure. This is, however, outside the scope of this paper.

Maintainability and availability modelling, beyond pertinence just involving time, will obviously involve suitable and adapted maintainability and availability assessment frameworks, where the underlying logic of it is expected to resemblance assessment frameworks e.g. as appearing in health care [4].

D. Time and location

Considerations related to maintenance involve time and location. When did a failure occur, where is it located, and what is involved. *Time and geographic location* of a fault on a higher level in the SoS relates also to Points-of-Interest (PoI) approaches in geographic information systems. *Location and description* of a fault is even more challenging.

Further, locations are often uncertain, and so is prediction of time in preventive actions. An important many-valued extension is therefore the generalization of points not just to sets of points, but indeed to many-valued sets of points of interest (MvSPoI).

E. Who profits and who pays?

On harvesting the wind, scale is commercial typically when over 100 kW, where electricity is sold rather than used onsite. In smaller scale, ownership related to that harvesting can manifest in form of lease of land, community ownership, or ownership of (a small) turbine. Note how land ownership is wind flow ownership, but for flowing water is different.

Intangibility of impact for consumers has become tangible as consumers are are reimbursed for loss of current in the energy supply chain. Consumer opinion must therefore be part of the pricing models. We no longer have a simplied numerical

$$\texttt{EnergyPrice}(supply, demand)$$

but also supply and demand depending on several factors, and logically explained as terms:

$$\texttt{supply}(s_1, \ldots, s_m)$$

$$\texttt{demand}(d_1, \ldots, d_l)$$

Several factors and phenomena affect this overall situation.

Construction and maintenance time and cable cost are typical. Excavation costs are also considerable, and in all, and the question about who bears all these costs remains unanswered. The cost of new distribution services are carried by developers, but may quickly be passed on to municipalities and in the end to consumers. Allocation of cost associated with placing cables underground is also unclear. Costs are absorbed in various points of the market chain, and if allowed by regulatory agencies, consumer will eventually pay.

The power price is still seen as a balance between between supply and demand. However, such pricing models overlook public opinion and policy making (Figure 2). Renewable resources of energy, that nobody owns as such, are transformed into economic resources, that are subject to the power market.

Regulatory agencies play an important role, and this combines with governmental policy making.

Restrictions enforced on the energy SoS by the regulatory agencies has as its objective to protect the interests of consumers, so that consumers are not to carry too much of the

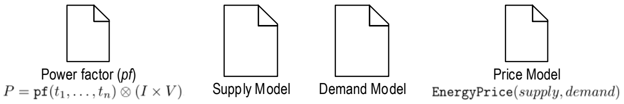

Fig. 2. Multifactorial energy price modelling.

burden arising from SoS improvements, in particular if improvement benefit consumers unequally. Regulatory agencies might also still base their delivery models using out-dated constructions, in particular in the case where there is a regional shift from overhead to underground transmission.

IV. CONCLUSION

We have described a many-valued logical framework for information ontology as part of business process structures. A main contribution is to show where uncertain but well-structured information resides within a process, and how information is canonically integrated rather than amalgamated in ad hoc approaches. Developments include a rigorous, yet flexible, modelling approach with energy supply as part of the energy market as whole involving all stakeholders.

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