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A Digital Twin for Risk Modeling and Decision-Support in a Smart Energy Grid

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Abstract: In this paper we use electrical grids and the energy market as a system-of-systems example including both digital twins simulating physical systems as well as energy distribution and the market constrained by laws and regulations. We show how activity processes and design structures can be viewed as having a common qualification modeling framework based on lattice-valuations. BPMN networks to are shown to resemblance DSM structures.

Keywords: Digital Twin, Electrical grid, Energy market, Lattice, Quantale.

1 Introduction

The idea of using digital representation of key aspects of physical objects or systems to make simulations in order to predict real outcomes of actions is not new. The term *Digital Twin* established by (Piascik et al, 2010) is relatively common today, but earlier terms like *Virtual Counterpart* can be traced back to (Främling et al, 2003) and perhaps earlier. The term digital twin is we choose to name our digital representations in this work. A digital twin is rarely just a static representation of a physical object or system, instead a digital twin needs to be able to represent the key actions its physical twin performs. In some sense a regular DSM may be considered a digital twin since key aspects of an object or system may be represented by the DSM and furthermore manipulated to produce some form of output, for instance an understanding of dependencies. In this article we enrich the DSM with lattice logic in order to make the manipulation of the representation easier.

Digital Twins have been used to simulate physical products behavior and lifecycles in various ways for a number of years but later use includes simulations of systems and system-of-systems from integrated circuits up to and above entire industrial complexes.

In this article we focus on how physical aspects of a real-life-system may be described in the same way as in a relatively basic DSM and how lattice theory can be applied to simplify and perform the logical operations needed to make simulations with a digital twin. In this case with the intent of simulating risk management for various business models. The benefit of this approach being the ability to use information with different kinds of scaling without losing stringency or deduction.

2 State-of-the-art

One interesting area to work with simulations of business models is electrical grids. The electrical grid is a complex system-of-systems with a large number of physical components and high demands for safety, reliability and availability. The actual product is not physical in the normal sense and could be classified as a service.

There are a number of established business models concerning electricity and the ecosystem of business models could be viewed as a system-of system themselves. These business models can be tailored for industries, housing companies, private persons, electricity traders, stem net owners, wind power plant owners etc.

The overall complexity of a digital twin of a smart electrical power grid may therefore wary greatly. From a strictly physical sense; there are city networks, usually with some division into sub grids, there are regional power grids, usually consisting of a number of city grids, which usually are fed by a number of power producers and often from a variety of production sources (Nordreg 2020). From a Swedish perspective those sources may be, Water power, nuclear power, wind power, sun power, coal power and more. The regional grids are usually connected into a national grid, at least in the sense that there is a national control center, TSO or Transmission System Operator, which surveils the overall production. In Sweden this TSO is called The Swedish national power grid, and it is in fact also the national stem network. It may not necessarily be possible to freely redirect the actual power output on a national level. The national power grid is often connected to an international power grid, in the Case of Sweden this is Nordpool, which interconnects the TSOs of14 European countries.

A modern power grid, almost regardless if a local or international focal point is chosen, will be minutely monitored at a vast number of points. Real time data with a known data quality will be available. This will not make it trivial to make a digital representation that could be deemed a digital twin of the physical aspects easy, but the basic ingredients are there. The challenge is to choose which data to include, time resolution and create suitable calculation models.

This article focuses on the challenge of making a digital twin that encompasses the business and governance models that drives and regulates the energy market. It is also important to point out that the energy market and business models as we see them today, for instance described in a joint report from the Nordic TSOs (Nordic Grid Development Plan 2019), may become much more complex in the near future.

The physical aspects of energy productions and distribution are subjected to a number of laws and regulations. The same goes for the energy market, where there in Sweden as an example is a governmental agency called Energimarknadsinspektionen– Swedish Energy Market Inspectorate, dedicated to govern the energy market. This means that there are at least five basic angles that a digital twin could be based on. The producer, the distributor and the seller are three. They could be the same but that is not necessarily the case, at least in Sweden. The last two could be named the customer and the government. Any of these five can draw benefit from a digital twin that can simulate various scenarios based on factors like risk, need and availability to help with decision support.

There are reports that state that a future market may be quite different from the traditional producer-consumer scenario. Apart from there being additional sources of energy, as according to a report from IVA - Royal Engineering Academy of Sweden (Byman, 2017), a more circular market is likely to occur where both private households and companies may produce energy from sun and wind, which will reduce their need and from time-to-time enable them to sell the surplus, if the energy grid and business models can handle that. There are also work being done in order to allow for better short and long term storage of electrical power. Electricity is typically a momentary resource, so this could affect the market greatly. There are some more visionary models that suggest that energy could be loaned, for instance from electrical cars, to handle momentary loads. This energy would then be returned at a later point. A successful digital twin must therefore also be adaptable and able to handle future business possibilities, since risk evaluation is a corner stone.

That risk management is part of the future energy market is described in another joint report from the Nordic TSOS from 2017.An important part of their work is to identify and quantify risk. We believe that risks cannot always be expressed in one simple scale and that it is important to be able to form new scales out of information from different scales

In this paper we show how lattice-valuation of design structure matrices enables to adopt lattice constructions for combining scales of information. We use BPMN (Business Process Modeling Notation) networks to show resemblance with DSM structures, and thereby we also show how lattice structures are useful more broadly for information assessment purposes.

3 Lattice-valued design structure matrices

In (Eklund, Johansson, Kortelainen and Winter, 2019) we showed how the “documentation of interaction between elements” as described in (Pimmler, 1994) and (Pimmler and Eppinger, 1994), and as based on the ordered chain,

$$L = \{Detrimental, Undesired, Indifferent, Desired, Required\}$$

or more shortly written as the isomorphic chain

$$L = \{-2, -1, 0, 1, 2\}$$

can be viewed within lattice theory. In particular, when that chain is detailed, e.g., for Spatial Scale, Energy Scale, Information Scale and Materials Scale.

We can now view this situation as having four different relations on the set X of elements, with relations, respectively, denoted $\rho_{Spatial}$, ρ_{Energy}, $\rho_{Information}$ and $\rho_{Materials}$.

We can additionally introduce the tupled relation

$$\rho = (\rho_{Spatial}, \rho_{Energy}, \rho_{Information}, \rho_{Material})$$

where ρ then takes the form $\rho : X \times X \to L^4$.

This product lattice L^4, consisting of 625 lattice values, is, however, not easy to work with in practice.

Note also how we indeed have a general situation involving the product lattice $L_1 \times ... \times L_n$ of separate lattices $L_1, \ldots, L_n$.

For $n = 2$, and the special case where L_1 and L_2 are the binary chains

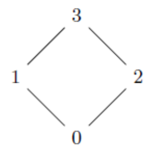
$\wedge$	0	1
0	0	0
1	0	1

$\vee$	0	1
0	0	1
1	1	1

the product lattice $L_1 \times L_2$ is the diamond

$\wedge$	0	1	2	3
0	0	0	0	0
1	0	1	0	1
2	0	0	2	2
3	0	1	2	3

$\vee$	0	1	2	3
0	0	1	2	3
1	1	1	3	3
2	2	3	2	3
3	3	3	3	3

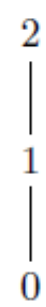


In the elements of the product lattice, 0 corresponds to the tuple (0,0), 1 corresponds to the tuple (0,1), 2 corresponds to the tuple (1,0), and 3 corresponds to the tuple (1,1).

If L_1 remains as the binary chain, and L_3 is the three-valued chain

$\wedge$	0	1	2
0	0	0	0
1	0	1	1
2	0	1	2

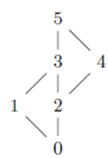
$\vee$	0	1	2
0	0	1	2
1	1	1	2
2	2	2	2



then the product lattice $L_1 \times L_2$ is the following 6-pointed lattice:

$\wedge$	0	1	2	3	4	5
0	0	0	0	0	0	0
1	0	1	0	1	0	1
2	0	0	2	2	2	2
3	0	1	2	3	2	3
4	0	0	2	2	4	4
5	0	1	2	3	4	5

$\vee$	0	1	2	3	4	5
0	0	1	2	3	4	5
1	1	1	3	3	5	5
2	2	3	2	3	4	5
3	3	3	3	3	5	5
4	4	5	4	5	4	5
5	5	5	5	5	5	5



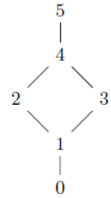
This shows how combining smaller and simpler lattices yield larger and more complicated lattices.

In this lattice, note how elements ‘1’ and ‘4’ can be viewed as being on the “sideline” of the subchain 0-2-3-5 of four elements. These sideline elements can e.g. represent unknown or for some other reason still not specified values.

The product is obviously not the only way of producing combinations of lattices. For example, let L_1 and L_2 be the 3-valued chains, and let $[L_1, L_2]$ denote the set of all six join-preserving self-maps from L_1 to L_2. If we equip $[L_1, L_2]$ with the order structure respecting pointwise order, then the resulting lattice is the following:

$\wedge$	0	1	2	3	4	5
0	0	0	0	0	0	0
1	0	1	1	1	1	1
2	0	1	2	1	2	2
3	0	1	1	3	3	3
4	0	1	2	3	4	4
5	0	1	2	3	4	5

$\vee$	0	1	2	3	4	5
0	0	1	2	3	4	5
1	1	1	2	3	4	5
2	2	2	2	4	4	5
3	3	3	4	3	4	5
4	4	4	4	4	4	5
5	5	5	5	5	5	5



These are two of a total of 15 (complete) lattices on six elements.

4 Business processes as design structures

BPMN includes five basic categories of elements, two of which are *Flow Object* and *Connecting Objects*. A set of Flow Objects can be arranged as relational matrix, a graph or a lattice, where attributes annotated with Connecting Objects serve as relational qualifications, edge characteristics, or lattice values.

Flow Objects are the main graphical elements to define the behavior of a Business Process. Among the three types of Flow Objects we will mainly consider *Activities*, and among the four different types of Connecting Objects we will consider *Sequence Flows* and *Message Flows*.

BPMN activities, as Flow Objects, are connected by Sequence and Message Flows, and further equipped with qualification lattices L_{SFlow} and L_{MFlow}. Activities seen as being related by those flows can be arranged as design structure matrices

$$\rho_{SFlow} : X \times X \to L_{SFlow}$$

and

$$\rho_{MFlow} : X \times X \to L_{MFlow}$$

In this situation we may again prefer to work with the tupled relation $\rho = (\rho_{SFlow}, \rho_{MFlow})$ either using the product lattice

$$\rho : X \times X \to L_{SFlow} \times L_{MFlow}$$

or, in case of $L_{SFlow} = L_{MFlow}$, we may use the lattice of join-preserving self-maps

$$\rho : X \times X \to [L_{SFlow}, L_{MFlow}]$$

Relational transitivity in a many-valued context is non-trivial. Given lattice values for $\rho(x_1, x_2)$ and $\rho(x_2, x_3)$, what is the lattice value, or desirable lattice values, of $\rho(x_1, x_3)$? Binary operations on lattices can be used to combine lattice values. Semigroups are useful in particular when the semigroup operation preserves left- and right-sided suprema. Such structure, *quantales* (Eklund , Gutiérrez García, Höhle and Kortelainen, 2018), provide a wide spectrum of logical operators over lattices.

"Sideline" elements, like described in the previous section, can be included in computation using the semigroup operation. A sideline element may also appear as a *unital* element e in the quantale, i.e., $x * e = e * x = x$.

There are totally 1268 quantales on the 6-point product lattice mentioned in the previous section. Of these, 60 are unital quantales, with 22 unital quantales having '1' as a sideline element, and 12 unital quantales having '4' as a sideline element. Below we show the tables for one of the unital quantales having '4' as a sideline element.

$*$	0	1	2	3	4	5
0	0	0	0	0	0	0
1	0	3	1	3	1	3
2	0	1	2	3	2	3
3	0	3	3	3	3	3
4	0	1	2	3	4	5
5	0	3	3	3	5	5

$\wedge$	0	1	2	3	4	5
0	0	0	0	0	0	0
1	0	1	0	1	0	1
2	0	0	2	2	2	2
3	0	1	2	3	2	3
4	0	0	2	2	4	4
5	0	1	2	3	4	5

$\vee$	0	1	2	3	4	5
0	0	1	2	3	4	5
1	1	1	3	3	5	5
2	2	3	2	3	4	5
3	3	3	3	3	5	5
4	4	5	4	5	4	5
5	5	5	5	5	5	5

Note here how $*$ can be interpreted as a logical operator, and a very different one as compared to the conjunction and disjunction provided within the lattice.

In (Eklund, Johansson and Kortelainen, 2019) we presented a general process view, Fig. 1, of the the energy involving energy sources and, policy-making and involvement of rules and regulations from national authorities.

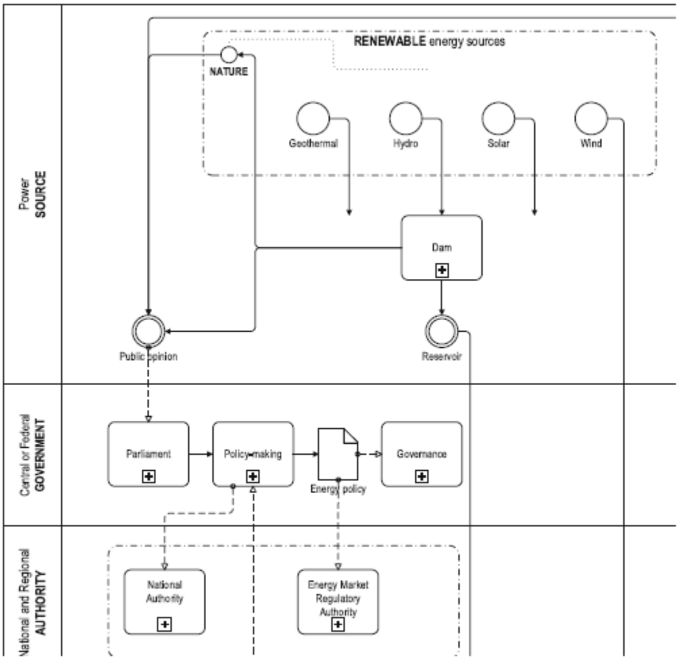


Fig. 1. BPMN overview of a regulated energy market.

This overall and briefly described subprocess has a focus on the energy market governance and regulation.

Suppose now that Sequence Flow is simplified to impose recommendation or obligation, seen as a 2-valued lattice

$$L_{SFlow} = \{rec, obl\}$$

and Message Flow is simplified to be seen as documentation delivered with certain granularity or degree of detail, represented by a 3-valued lattice

$$L_{MFlow} = \{low, standard, high\}$$

In the unital quantale selected above, the unit is $(rec, high)$, which would mean that a pathway flow from Parliament to Governance would not alter a highly detailed recommendation when Parliament messaging shift (BPMN) Swimlane to Authority.

This is a very simple example, but nevertheless shows how the semigroup operation may be fixed for a whole process, or fixed for certain subprocesses crossing Swimlanes. The application at hand, and decision-support objectives will make final selections of quantales applied when and where in the overall process.

5 Conclusion

We argue that there in the future will be a need to represent and manipulate information from a variety of sources in tomorrow's energy market. An increasing number of power sources, micro transactions and power users will make the need to simulate various outcomes. Bothe producers and customers may see the need to perform in-depth analyses of a combination of business models. There are a number of things that can be simulated but in this case we aim to show that one key aspects would be risk modeling for decision support in a diverse energy market. Operations on lattice-valued design structure matrices is one way to reduce complexity of these operations. We also argue that this may be of use both to customers and producers, who sometimes may be the same organization, as well as for governmental actors. The basic methods we show, combining DSM nomenclature with BPMN representations of design structures, are earlier work but in combination with algebraic-structures we get a new way of describing relationships that may also be used for simulations. In this case simulations of risk management that also enables direct comparison with established DSM methods.

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