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System Dynamics: Framework & Practice for Systems Modelling

D6.1 (Companion Report)

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Deliverable

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System Dynamics: Framework & Practice for Systems Modelling

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DISSEMINATION LEVEL

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Statement of Originality

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Summary

Over the course of the project, UNIVBRIS and partners will build on established expertise in Systems Thinking and Engineering to facilitate the collaborative development of meaningful models of emerging energy futures. These models can help stakeholders understand better the potential of TwinERGY's innovations and optimise the use its outcomes. To that effect we first develop a framework of practice for group model-building of energy systems, utilising System Dynamics (SD) as a core technique.

Through the use of SD and the techniques discussed in this deliverable, various stakeholders will be able to engage in a process of collaborative model-building, where causal loop mapping predominantly, as well as stocks-&-flows modelling where applicable, will provide qualitative and quantitative means for developing rich insights into the future energy marketplace. The TwinERGY modules and platform functionality will offer the required support so that such models can be 'codified' and tested as scenarios in the real world, so that insights into the impact of our emerging technologies can be developed. Other techniques are also documented in this companion so that individual pilots or other stakeholders appreciate their potential relevance and use for energy systems modelling.

Alongside these, exploration of interdependencies in TwinERGY's Systems Architecture and potential impacts of unintended consequences will be enabled by the application of matrix-based tools such as N-Square Diagrams, or strategic exploration and problem structuring methods such as the Soft Systems Methodology (SSM). These enable the identification of scenarios where cascading effects of changes at local/component level may compromise the ability of the whole system to function and deliver as expected. In this deliverable we formulate a programme of work utilising these that will enable consortium partner to work with pilot participants and other key stakeholders to address issues as discussed.

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1 Introduction

Engineered artefacts at the heart of the TwinERGY approach, such as Digital Twins and Distributed Ledger Technology, the notion of Transactive Energy or the use of Machine Learning/Artificial Intelligence, have the potential for transformational impact of the status quo in the energy sector. However, whatever definition one adopts for these, it is a fact that they represent an element of added complexity. Exploring the interdependencies of these technologies, their potential unintended consequences, identifying and articulating benefits from, whilst de-risking their use is therefore a fundamental task, in line with the ethos of responsible innovation that is pervasive through our overall approach.

As the pilots are entering their enactment stage, our volunteer participants are signing up and the technology is delivered across sites, the above process will be ongoing and based on collaborative methods and techniques. These will be representative of approaches commonly used to structure complex socio-technical problems and to develop common understanding, and hopefully purpose, between stakeholders such as the participants, researchers, technology developers, municipalities, the state, other project consortia, industry representatives etc. Building upon our overall methodological framework we will further define here the thinking and modelling tools that will be used to engage stakeholders over the duration of the project, through a structured programme of work and key interactions including relevant activities such as meetings and workshops.

Energy sector stakeholders, as have been identified through TwinERGY actions, will come together to reflect on energy futures, their role and common purpose through strategic exploration and problem structuring and by reflecting on modelling artefacts that have been developed collaboratively. Working at local, national and international level a number of representative modelling artefacts will provide the basis for examining real world scenarios implemented in TwinERGY and understanding their value and impact. To that end a number of methods and tools from within the broad family of Systems Thinking will be used to facilitate the process and capturing the dynamics and interdependencies of the field. The following sections introduce an outline of the thinking framework and provide examples and a plan of engagement with stakeholders over the remaining of the project.

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2 Tackling the Energy Future's Challenges with Systems Thinking

2.1 Setting the Challenges

The grid-based energy system that contemporary society depends upon is a complex web of supply and demand that stretches at least over an entire state. Much of TwinERGY activity focuses on the demand side of that system, consisting mostly of energy used in buildings. We refer to it as the 'energy demand system' – the part of the energy system that lives 'behind the meter'. The central supply side, which includes central generation, transmission and distribution of power (i.e., the remit of the traditional Grid) is not considered in this companion.

The energy demand system is highly diverse across sectors, multi-layered, highly influenced by the psychology and sociology of people, and complex in the diversity of applications of energy-using technologies – in other words, reducing demand is a 'wicked' problem (Conklin, 2005). This is illustrated by the fact that although e.g., energy efficiency is being implemented on a wide scale throughout the UK, almost 10 years ago in 2009 energy demand in the transport and residential sectors was 21% and 13% higher, respectively, than 1990 levels, and domestic per capita consumption was only 1% lower than in 1990 (DECC, 2010). More recently and with the impact of the Covid-19 pandemic still ongoing, the quarter April to June 2021 saw overall demand in the UK increasing 23% over the same period in 2020 (BEIS, 2021).

Typically, demand reduction interventions have mostly sought to address single issues such as end-use equipment efficiency and operation, energy behaviours, or distributed generation, but there have been calls for a more integrated approach. Wilson and Dowlatabadi (2007) envisage a goal of entrenching the 'social and behavioural determinants of energy use as a wholly integrated part of energy efficiency research' which indicates a systems approach of some kind. We argue that many of the methodologies and concepts in the field of Systems Thinking (ST) are appropriate tools when working on the demand side.

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In particular, there two separate but related challenges which ST could be used to help answer (Freeman & Tryfonas, 2011)

1. What is the nature of energy demand and can we identify how transitions happen within it so that we can influence it?
2. Can we develop better interventions to reduce energy demand at the user level, which see each household or organization as a system that includes technology, buildings and people and work with the interactions between these components?

2.2 Scoping the System of Interest and Understanding its Context

Key environment for energy use in the context of TwinERGY is the domestic and commercial built environment. Figure 1 shows how this System of Interest (SoI) is perceived within its larger operating environment.

- Within the system boundary there are five main categories of components:
    - people (consumers/prosumers),
    - energy service demand (need for warmth, light, motor power, etc.),
    - energy-using equipment that provides services (boilers, light bulbs etc.),
    - low-carbon energy generating or storage equipment (solar PV, CHP, batteries etc.), and
    - intervention strategies (energy behaviour change, energy efficiency upgrades, etc).
- The SoI sits within the Operating Environment of wider society, made up of many components which affect how it operates, as well as providing inputs that allow the system to function. The outputs from the SoI are the emissions associated with energy use. This is the metric that typically most interventions seek to reduce.

At this level, a unit of analysis could be perceived the single household or organization, and the components of the system are of two types: hard or soft. Hard subsystems are the physical building(s) and energy using equipment in them; soft subsystems are the (one or more) collection of people that buy and operate that equipment. Presented here are ways to identify meaningful subsystems and some of the ST methods that could be used to work with them. Depending on use-case focus, the system boundary can be recognised around such unit (e.g., a single household) or a collection of households that form a community (and is built upon multiple collaborating units).

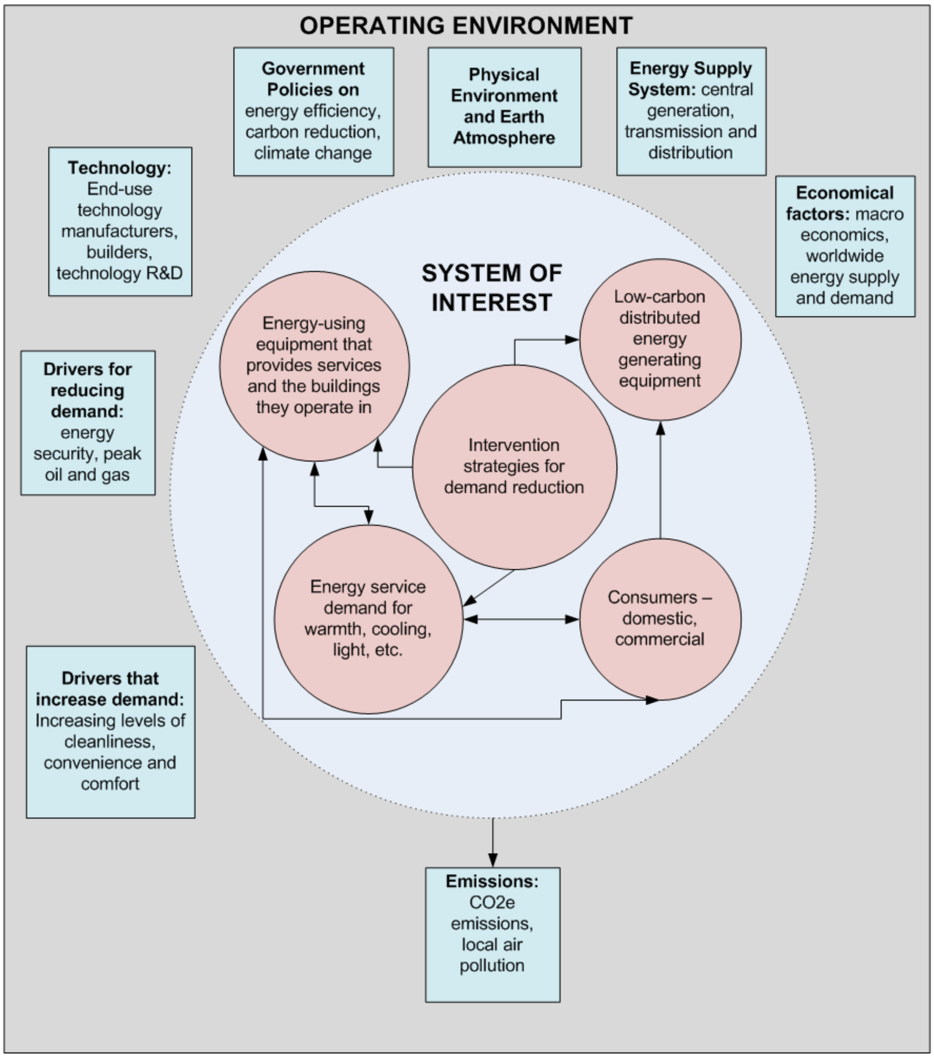

Figure 1 – The SoI and its Operating Environment

In order to be able to better understand how contextual developments and external drivers such as policy and regulation frameworks, new technology development and societal needs that stem from events such as climate change, the Covid-19 pandemic etc., it will be helpful to analyse the SoI within a conceptual framework. We formulate an overall approach that enables collaborative exploration of the nature of energy demand and how TwinERGY innovation can shape developments in this landscape based on group model building practices, utilising Causal Loop Diagrams and the process of the Soft Systems Methodology.

2.3 Intervening at Subsystem Level

There are many different ST methodologies, developed in and suited to particular types of systems or problem spaces. Jackson and Keys (1984) developed a way of categorizing both problem contexts and the methodologies suitable for them in their 'system of systems methodologies'. Within this classification scheme systems are either mechanical (relatively easy to understand), or systemic (manifesting difficult problems). Participants are unitary if they all agree on a common set of goals, and pluralist if they have differing objectives. All problem contexts can be assigned to one of four categories: mechanical-unitary, systemic-unitary, mechanical-pluralist, or systemic-pluralist.

Care must be taken in using this categorization system due to the danger of it leading to the application of a method from one paradigm to a problem space that exists in another (Jackson, 1990). However, the approach is a useful tool in identifying and classifying subsystems within the larger SoI. Two examples follow.

- A house's heating system is mechanical-unitary – the system components are well known, and the users have a common objective (maintain comfortable indoor temperature throughout the house).
- A school and its stakeholders (including the buildings, staff and pupils, facilities management, and outside interests such as Local Authority) is systemic-pluralist – participants may have differing priorities as far as use of equipment and the buildings are concerned (energy costs, indoor comfort, convenience, educational needs, etc.). The system is complex and has emergent properties – like when post-occupancy energy demand is higher than was planned for during the design stage by architects and builders.

Both examples above include 'hard' subsystems – e.g., heating and lighting systems in buildings; motors and appliances; the building envelope (windows, walls, etc.) – that could be optimized with the use of the traditional Systems Engineering (SE) approach. The benefits of SE are that it is inter-disciplinary, it enables complex systems to be modelled and organized, and it considers component interaction – like that between the interior layout of a building and its heating system performance. SE can be used in specific projects to identify synergies between different energy saving technologies, analyse technology-people interactions, do economic and energy trade-offs, define system requirements, identify feedback loops, and determine when to use automated controls versus manual controls (e.g., Matar et al., 2017; Geyer et al., 2014; Liu et al., 2010 etc.). For example, designers can either ask staff to turn lights off when not needed or install daylighting controls that ensure lighting only comes on when there is insufficient daylight. Within TwinERGY, the adoption of the Smart Grid Architecture Model (SGAM, EC 2012) as an architectural framework typifies this application of traditional SE, as already discussed in deliverable D4.3 (Methodological Framework).

But further to the delivery and optimisation of the individual technical components, the impact of how technology is used on overall energy consumption and building comfort can be significant. For example, a report on developing low carbon schools, states that 'poor behavioural patterns and misuse may lead to the energy consumed in a school building being up to 45% higher than predicted.' (Prodromou et al., 2009). To understand how people interact with technology and make decisions about its use, different models of energy decision-making have been developed in the fields of psychology, conventional and behavioural economics, technology diffusion, and the social sciences. However, because of the heterogeneity of energy decision making throughout the whole population, these models may apply only in specific behavioural niches – determined by where they live on the individual-to-social, instinctive-to-deliberate, psychological-to-contextual, and short-to-long term continua (Wilson & Dowlatabadi, 2007). Based on these behaviour models, various types of energy behaviour change (BC) campaigns have been run with genuine but modest effects proven; evidence points to increased effectiveness when BC campaigns are targeted towards specific sub-groups and the need for consistent messaging.

We have made a decision to base our model building on System Dynamics techniques, in particular Causal Loop mapping. As we discuss in more detail below, the nature of these models allows for multiple individual stakeholders to engage with their development, facilitating at the same time the development of common understanding of shared issues. This technique emphasises on qualitative and visual modelling, so it is appropriate for the engagement of stakeholders at any level (user/participants, industry representatives, project partners etc.). It is also relatively straightforward to convert such models to quantitative and data driven simulations (stocks and flows system models) that could complement the functionality of the Digital Twin and provide additional validation means for TwinERGY's key outcomes. Such models could be developed further upon consumption data generation from the pilots.

The planning, development and subsequent use of such models through-life of the project is coordinated through the use of an overall Systems Thinking framework, the Soft Systems Methodology, the brief background of which is provided later in this document for reasons of completeness.

System Dynamics (SD) – Causal Loop Diagrams (CLD)

A system can be defined as an arrangement consisting of physical components that are connected or related in such a way that they act as an entire unit (DiStefano et al. 2011). Kump et al. (2011) defines a system as an entity that is composed of diverse parts (components) that are interrelated. Together they function as a complex whole. A system may also exhibit adaptive, dynamic and evolutionary behaviour (Meadows, 2008). DiStefano et al. (2011) go on to define a control system as being an arrangement of physical components that are connected in such a manner as to regulate itself or another system. Given this definition, it could be argued that the physical and build environments are abound with control systems. Note also that this is an idea central to the notion of the Viable System, where control is also a recognised element of it.

A systems approach can be applied in virtually any area of inquiry (Kump et al., 2011). By studying the environment in systems terms and gaining an insight into its behaviour at a particular moment in time, it might be possible to build a more accurate picture of both the past behaviour of a physical system, whilst making more accurate predictions about the future. This can be especially important, for example, when considering the extent to which anthropogenic activity is responsible for modifications of the environment and the consequences of such change.

Components of a system interrelate in such a way as to determine the state of the system by allowing for the flow of information from one component to the next via links known as couplings (Kump et al., 2011). Both positive and negative couplings can exist. In the case of a positive coupling, a change in one component, leads to a change in the same direction in the connected component, e.g., an increase in insolation could directly result in an increase in the Earth's surface temperature. Conversely, in a negative coupling, a change in one component would result in a change in the opposite direction in the connected component, e.g., an increase in surface albedo would directly result in a reduction of the Earth's surface temperature (Kump et al, 2011).

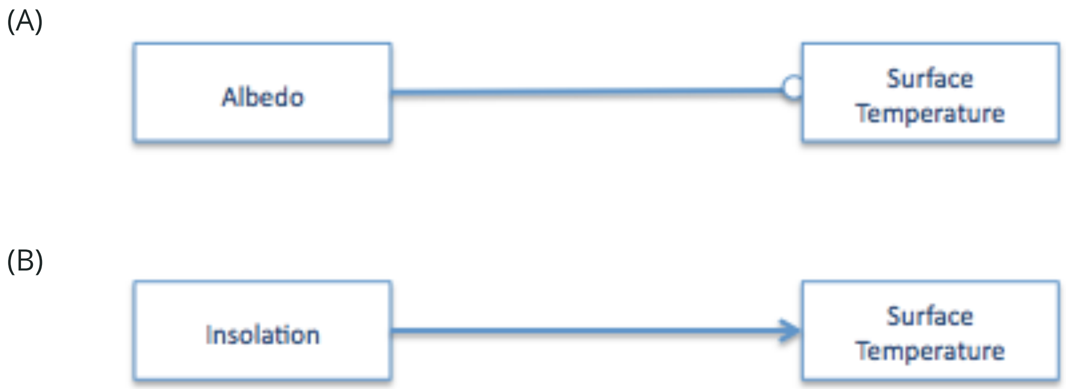

Figure 2 - An example of a negative coupling (A), where an increase in albedo results in a reduction in surface temperature and a positive coupling (B), where an increase in insolation results in an increase in surface temperature.

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Couplings may also result in a feedback loop, which can be defined (Kump et al., 2011, p.22) as a "self perpetuating mechanism of change and response to that change". Feedback loops may also be negative or positive, where negative loops reduce the effects of the disturbance and where positive loops amplify the effects. Figure 3 shows an example of a positive feedback loop where an increase in albedo results in a reduction in surface temperature. In turn, this increases ice-cover, which also has the effect of increasing the albedo.

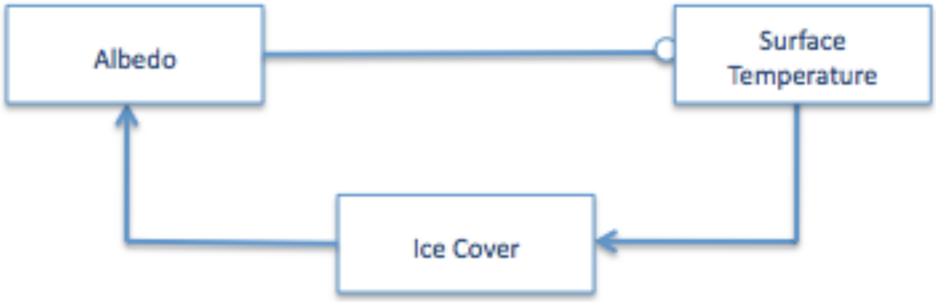

Figure 3 - An example of a positive feedback loop, where an increase in albedo results in a reduction in surface temperature, allowing ice cover to increase which, in turn, further increases albedo.

A system is described as being in a state of equilibrium when it does not change until something creates a disturbance. Equilibrium may be either stable or unstable. In a stable state of equilibrium, a small disturbance to the system will result in responses that will quickly return the system to a state of equilibrium. In a system in an unstable state of equilibrium, however, a small disturbance may result in system adjustments that carry the system further and further from its original state until a new state of equilibrium, if such a state exists (Meadows, 2008).

Looking, then, in a system with a single feedback loop, a negative loop demonstrates a state of stable equilibrium whilst a positive feedback loop demonstrates a state of unstable equilibrium. In the case of built environment and energy systems, such as in the domain of our project, however, the reality is considerably more complex. Systems such as these are typically made up of a combination of several subsystems that may consist of both positive and negative feedback loops.

A perturbation of a system is a temporary disturbance of a system, whereas a forcing mechanism is a more persistent disturbance. Kump et al. (2011) give as an example of a perturbation in natural systems such as the volcanic outgassing of sulphur dioxide into the atmosphere during a terrestrial (Earth) eruption. As SO_2 reacts to form sulphate aerosols in the atmosphere in the period following the eruption, it prevents a small amount of insolation reaching the Earth's surface, lowering average global temperatures. Forcing mechanisms, on the other hand, such as increasing levels of sunlight received by the Earth over billions of years, are more persistent in nature.

We referred to how thinking in systems is comprehensive in terms of providing the ability to encounter both the natural, but also the built reality. The ideas of feedback loops, control, mechanisms of disruption and forcing etc. can be fundamental to describe the behaviour of engineered systems. As an example, Shepherd (2014) outlines the fundamental principles and possibilities for application of system dynamics in transportation modelling. System dynamics is a methodology that uses a standard causal loop approach to develop qualitative models of a system which could be used to develop dynamic hypotheses before a more quantitative stock-flow model is developed (Shepherd, 2014).

The approach can be used to model various transportation scenarios, such as the uptake of alternative fuel vehicles, highway maintenance and construction, and airlines and airports. This approach is particularly suited to problems with feedback and recurrence, e.g., in particular of the 'problem symptom – quick fix – problem growth' type, such as the interrelated transport variables 'congestion – capacity – car use'. The potential problematic nature of increasing the capacity to fix issues of congestion, is that it could then lead to increased car use. This then aggravates the initial problem of congestion, resulting in a repetitive and non-progressive cycle occurring within this loop. Figure 4 below demonstrates this idea; the positive polarity label indicates an increase in one variable as the variable at the start of the arrow increases, and the negative polarity label indicates a decrease in one variable as the variable at the start of the arrow increases.

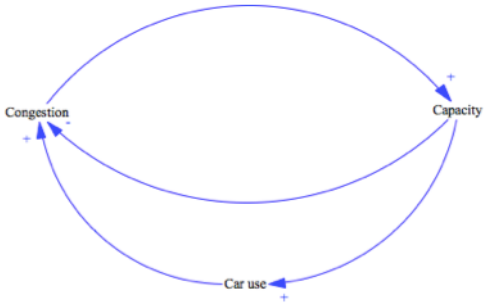

Figure 4 - causal loop diagram of the congestion – capacity – car use problem, created in the Vensim tool (as mentioned in Deliverable D4.3).

The causal loop shown above has been included as a fundamental or archetypal loop within the detailed model of a broader transport system shown in Figure 5. The variables of congestion, capacity and car use have a significant influence on the feasibility of transport improvements, and the potential for reducing air pollution. The relative levels of these variables also have a large impact on many others involved in a typical transport system, such as traffic, active travel use, and travel time, all of which are also identified in Figure 5.

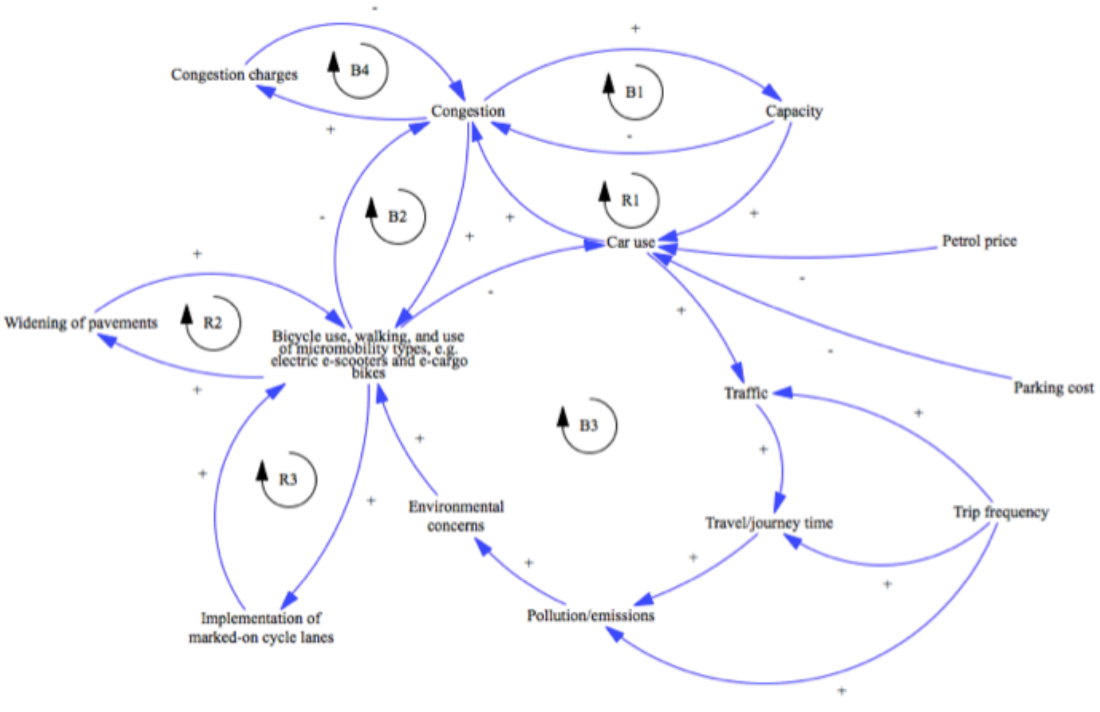

Figure 5 – causal loop diagram of a typical transport system.

EXAMPLE: Modelling skills demand for Smart Local Energy – Case of Bristol City (EnergyREV project)

EnergyREV is one of the three key components of the UK Industrial Strategy Challenge Fund's Prospering from the Energy Revolution (PFER) programme[1]. A significant proportion of this funding has been invested in three large scale local energy system demonstrators across the UK. Researchers from the University of Bristol analysed the local energy landscape and in collaboration with local stakeholders explored the future skills needs for Smart Local Energy systems to succeed (Chitchyan and Bird, 2021). Using

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[1] https://www.energyrev.org.uk/about/

causal loop diagrams as a technique to capture key interrelationships and positive/negative feedback loops.

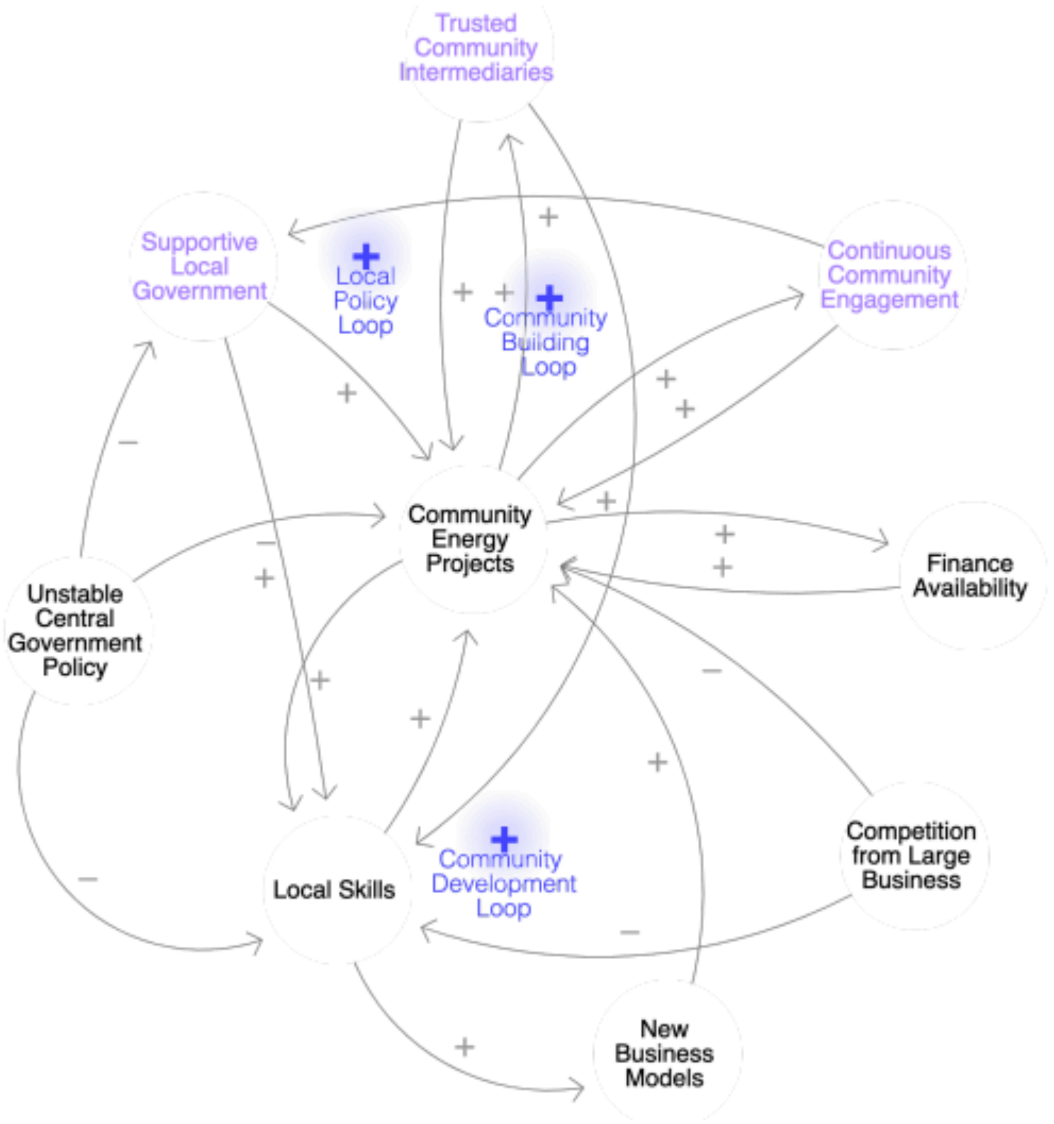

Figure 6 – Causal model of Bristol's Community Energy Subsystem (factors local and specific to Bristol are presented in purple) – as appearing in (Chitchyan and Bird, 2021).

The model of Figure 6 is a qualitative dynamic model that can be used as part of examination of scenarios in workshop and other collaborative settings (a link to access the model is available[2]). Through it, the impact of a number of variations of contextual factors such as levels of funding availability or community engagement can be understood through the execution of simulated scenarios.

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[2] https://energysystems.blogs.bristol.ac.uk/2021/03/08/community-energy/

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Soft Systems Methodology (SSM)

The use of Digital Twins, blockchain applications and other innovations developed in TwinERGY address sociotechnical problems that cross the boundary between human activity systems and engineering artefacts. These often involve many interested parties with different perspectives (world views), where ill-defined issues could cause difficulty in agreeing objectives (success requires stakeholder consensus). Being able to bring stakeholders on tha same page and allowing the development of common understanding of the challenges is therefore crucial.

Several Systems-oriented methodologies could be applied to facilitate collaborative energy problem exploration and solving. They can be differentiated between those based on ST (that rely on diagramming and analysis) versus those that work in a systemic way (that rely on action research and allow for emergence). Representative examples include:

- Checkland's *Soft Systems Methodology (SSM)* (Checkland & Scholes, 1990) is a ST method that establishes a learning system for investigating messy problems and enables practitioners to 'bring to the surface different perceptions of the problem and then structure these in a way that all involved find fruitful' (Chapman, 2004). It has been demonstrated useful for collaborative behaviour change within organizations.
- Kurtz and Snowden's *Cynefin Framework* (2003) is a ST model applicable to complex adaptive systems and their inherent uncertainty. The methods, based on this framework[3] are derived from complexity and narrative principles and include techniques such as Metaphor Simulations, Social Network Stimulation, and Archetypes. These methods are useful when working to evolve the functions of an organization.
- *Action research* is a systemic approach that allows for a looser exploration of organizations and how their operations transform. The LowCarbonWorks project (Reason et al., 2009) used action research to investigate four case studies of carbon reduction within organizations. Case study results were successfully mapped to the MLP, and tools for using action research to collaboratively achieve carbon reductions in the commercial sector were developed.

Although all three are flexible enough to be adapted to an energy-focused intervention, we will particularly adopt principles of SSM as, besides our team's familiarity with it (e.g.,

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[3] https://thecynefin.co/

Craig et al., 2014), it is a method that integrates naturally with Systems modelling techniques, including System Dynamics and even potentially the Viable System Model (later introduced in the appendix). The former has been selected for facilitating the Systems modelling of TwinERGY's interventions for the development of common understanding between involved groups of stakeholders. This is gradually developing through activities and relevant dissemination actions (academic publications, workshops etc.) broadly planned under the principles of SSM.

SSM is an action-oriented process of inquiry in which stakeholders formulate a solution strategy from a systemic understanding of the problem situation and take action to improve it (Checkland, 2013). SSM has had considerable success as a problem structuring methodology and has been applied to learning systems (Checkland & Scholes, 2000) and information system design (Curtis & Cobham, 2008). SSM addresses unstructured ('soft') problematic situations where there may be little consensus among stakeholders (even about the actual problem). SSM aims at accommodating different perspectives through conceptual models of human activity systems. These models are then used to decide on interventions for the resolution, or improvement, of the situation.

SSM focuses on the development of a conceptual model (a view of what could exist) with the aim to express stakeholder mental models of the problem and gain consensus on objectives and issues. A problem may even disappear as the result of stakeholder consensus on a number of key issues. A concept model does not describe what exists but is modelling a view of what exists within a human activity system. When models are used in the design of information systems intended to support physical processes, a comparison between the models and the physical world is required. During SSM analysis, a 'soft' problem will be expressed to provide a perspective that can be considered a 'hard' problem to be solved by a variety of traditional methods. Checkland argues that SSM could be used to address systems engineering problems, as the ability of SSM to address 'soft' problems is akin to Operation Research which solves structured 'hard' problems (Checkland & Scholes, 2000). SSM can be an iterative process to drive continuous improvement (Deming, 1986).

Traditional SSM is broken down into seven stages:
1) Entering the unstructured problem domain,
2) Expressing a structured problem situation,
3) Formulating root definitions of relevant systems,
4) Building conceptual models of human activity systems,
5) Comparing the models with the real world,

6) Defining changes that are desirable and feasible, and
7) Taking action to improve the real-world situation.

At this initial stage, where TwinERGY Pilots are in the process of procuring technologies and the technology partners are formulating the core technologies for deployment, of particular importance are the first three steps as outlined in turn.

A. Unstructured Problem Domain

Framing the problem situation, understanding the context (and culture), and identifying actors is the first stage in SSM. A rich picture is an unstructured way of capturing information, and communication within a human activity system. Initial interactions of pilot partners, participants and where applicable external stakeholders facilitate the building of common understanding through life of the project. We have started this process here by employing CLDs as a means to developed joined up thinking and by developing archetypal models of our system.

B. Problem Expression

The second stage in SSM examines the relationships within and between structure and processes. People, process and technology form the activity system of an organisation, that are dynamically entangled, rather than self-contained entities with discrete interactions. Deming states that “If you can’t describe what you are doing as a process, you don’t know what you are doing!”, therefore our approach should be captured within a model (Deming, 1986). Here, by reference to the System architecture and via use of the N-Square charting technique we examine these relationships between system setup and structure and process, esp. information exchange and what needs to be known by which subsystem, in order to identify key interdependencies.

C. Root Definitions

A root definition of a system (relevant to the problem) is a clear statement of purpose, that identifies the stakeholders, processes and value of the System of Interest. A ‘CATWOE’ analysis of the root system(s) identifies the **C**ustomer (who are system beneficiaries), **A**ctors (who transform inputs to outputs), **S**uppliers (who provide input resources) and **O**wner (who has the power of veto), the **T**ransformation process (purpose of the system), **W**orldview and **E**nvironmental constraints are expressed (acronym terms expanded not in order here).

N-Square Diagrams

Decomposition into subsystem entities can facilitate handily the analysis of interdependencies, both in terms of identifying such and in designing for robustness. A simple but powerful technique to do this is to place all such entities on a diagonal and identify all item flows between them. Traditionally we can identify outputs in the horizontal dimension and inputs in the vertical. Then we can reorder these to group tightly coupled elements (i.e., where there is heavier interaction occurring). In this way, nodes of interest (critical functions, nodal points etc.) become clearer to identify.

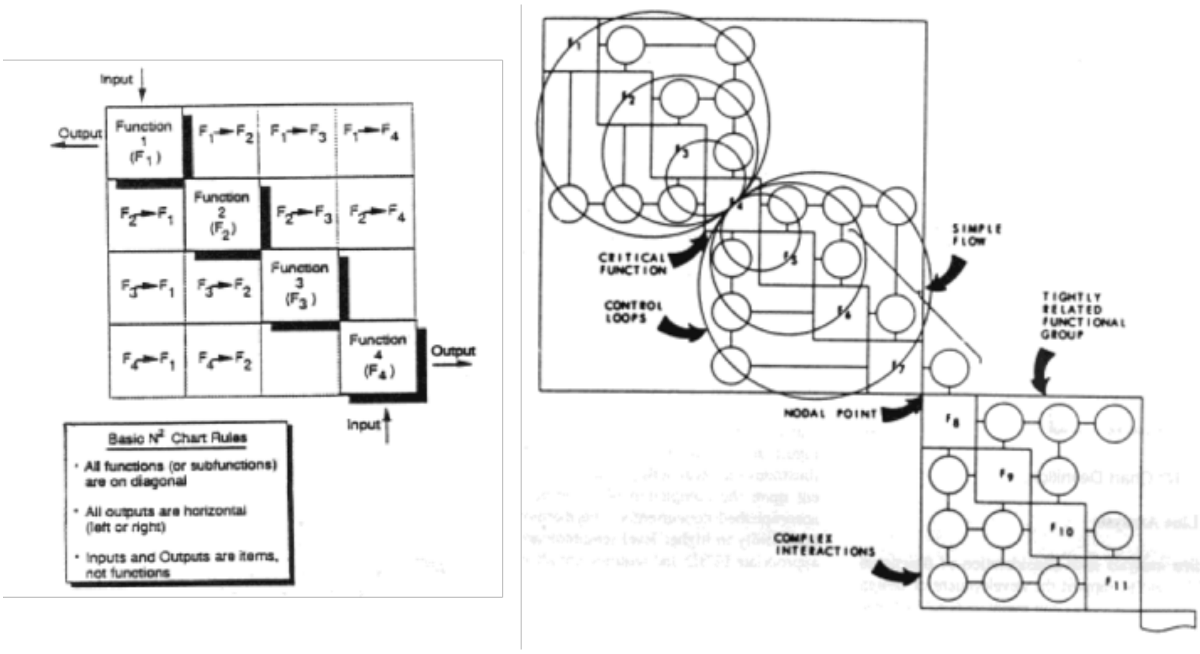

Figure 7 – N2 diagramming of key system functions (NASA SE handbook, pp. 129-130).

For example, in modelling a building as a system, a N-Square diagram exploring the interdependencies of four key energy management subsystems (HVAC, Lighting, Electrical and potential co-generation) could look like Table 1 (Dawes, 2016). We later introduce in the Appendix an example of more elaborate modelling based on this for the interested reader.

Table 1: N-Square diagram showing intra-system interactions within the Energy Management System of a building

Energy Management	HVAC		•Increase conditions to the greatest values within a specified range which allows energy usage to be shed during peak hours.	• HVAC can 'outsource' a needed increase in temperature, without drawing more energy from the grid.
		Lighting	• Maximise the amount of natural light, to minimise the energy used.	• If more light is required, and the grid energy cost is high, generators can provide electricity, the heat from which can be used in the HVAC system.
			Electrical Load Shedding	
	• If high grid power cost occurs, then the heat from the generators can be fed into the HVAC system.		• Reduce need for grid power in HVAC system during periods of peak energy cost.	Cogeneration of Electricity

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3 A Systems Approach for Modelling TwinERGY

Systems modelling methods and techniques as described in this deliverable can provide advanced insights into complex issues. We plan to utilise the techniques throughout the project to understand the developing dynamics and impacts of TwinERGY's interventions. The first step however is to develop archetype systems capturing the essence of TwinERGY's testbeds. To that end we will use causal loop diagrams (CLD) to model the participant household testbeds, working collaboratively with local pilot partners and selected pilot participants, in order to co-develop models built upon common understanding of the system and its interdependencies.

3.1 Causal Loop Diagram Examples from Bristol

Development of basic testbed models and scenarios based on CLDs started with internal group meetings considering individual components and their interdependencies, e.g., a battery that is charged through a photovoltaic panel (PV) exposed to sunshine etc. E.g., Figure 8 shows a preliminary hand-drawn model on an online whiteboard during a hybrid meeting to consider the boundaries of the local testbed in relation to each household and the energy market.

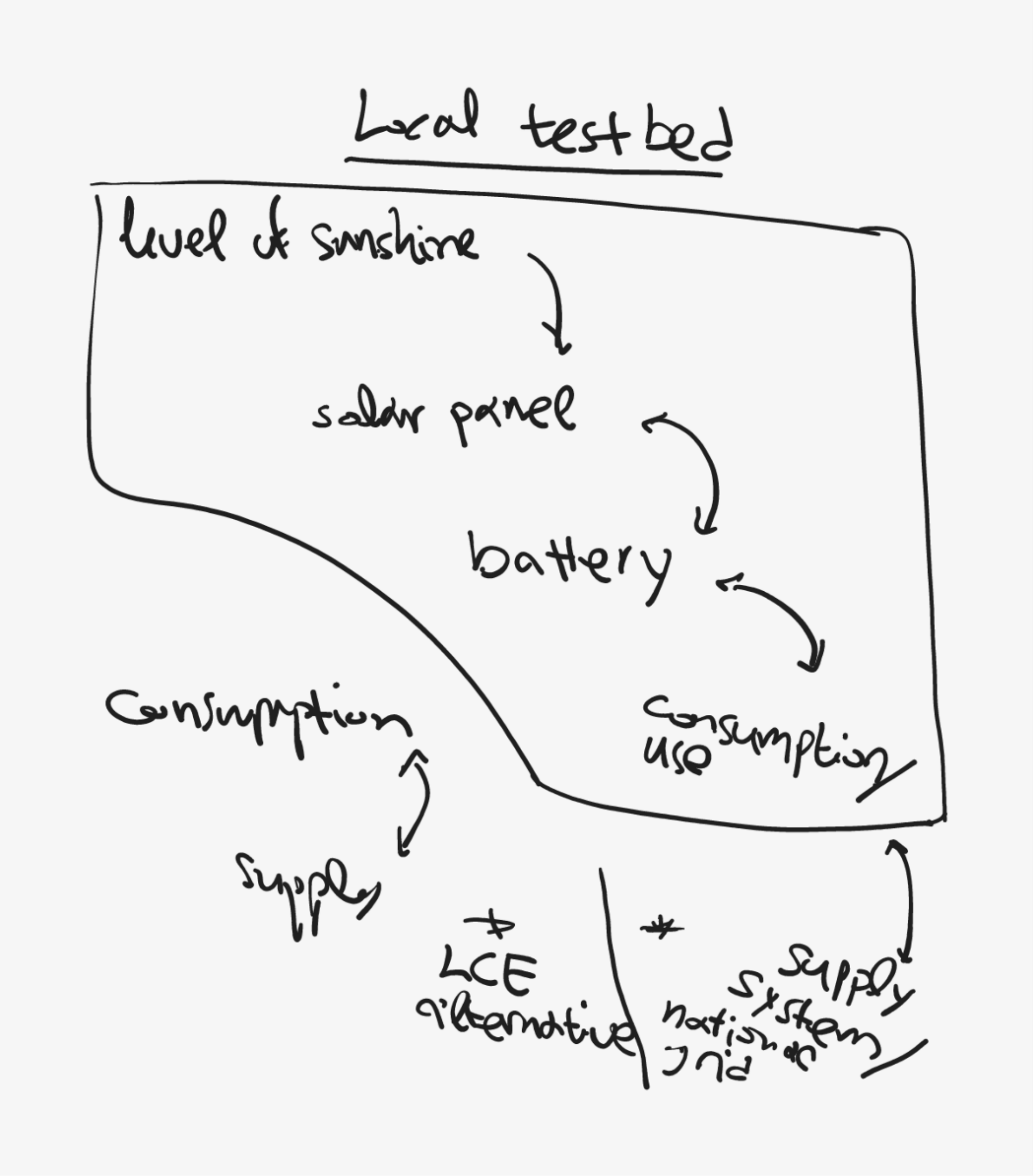


Figure 8 – Collaborative online whiteboard sketch (MS Teams) from initial group model building

In turn, this model produced a *Systems Archetype* (Figure 9) of our specific testbed, i.e., a basic manifestation of how the assembly PV/battery/TwinERGY will behave as an integrated system producing the desired effects. On this model, certain features have been recognised as input parameters (e.g., occupancy, level of sunshine, appliance efficiency) and others as interrelated variables that cause complex behaviour (e.g., PV generation, battery charge, consumption, grid imported energy and ultimately cost). In the scenario captured in Figure 9 we have assumed use of a simple fixed tariff (hence there is no input for the cost of a unit of energy). It is easy however to represent a variable tariff via the addition of another input representing unit cost (and affecting positively the overall Cost).

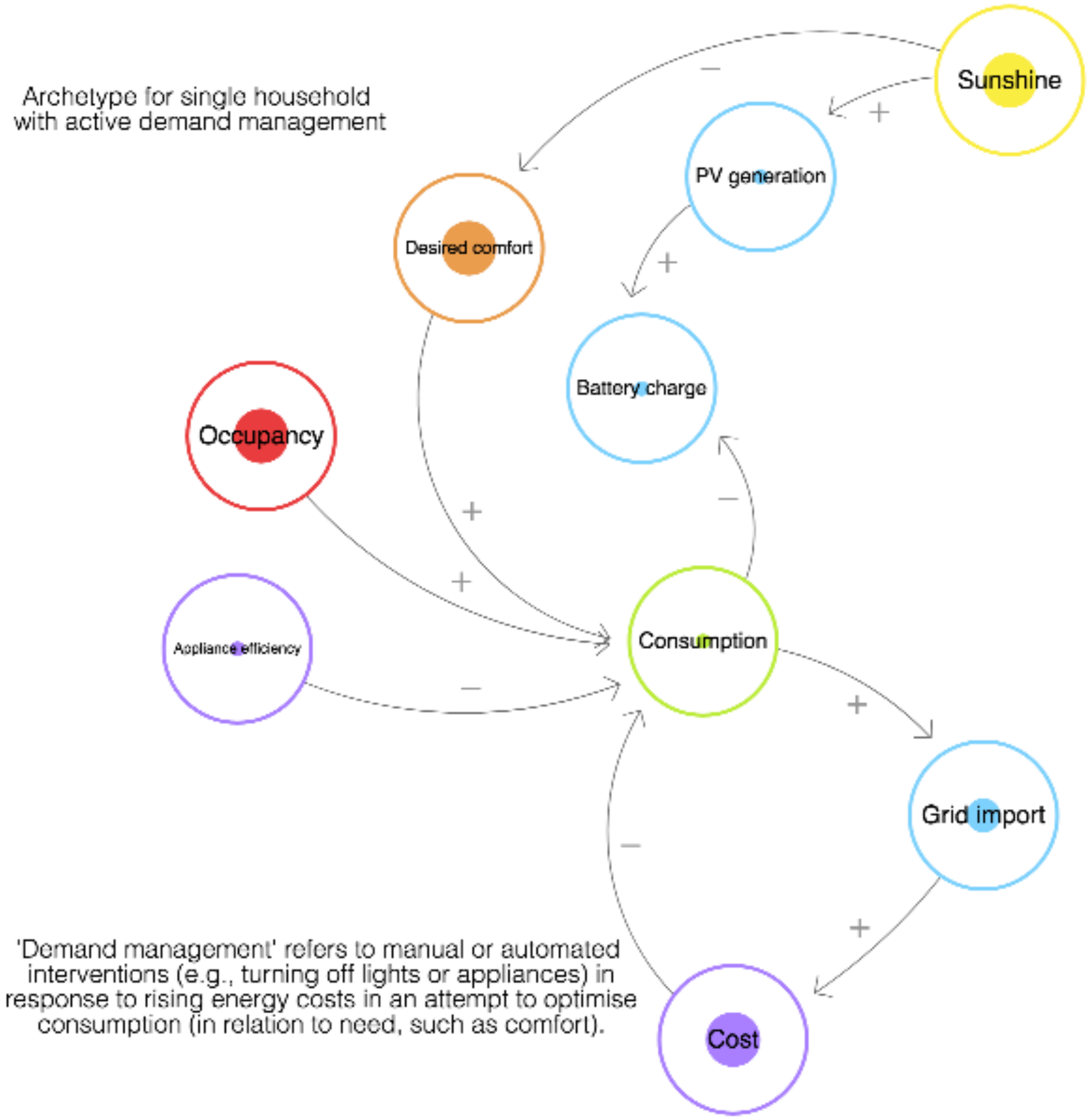
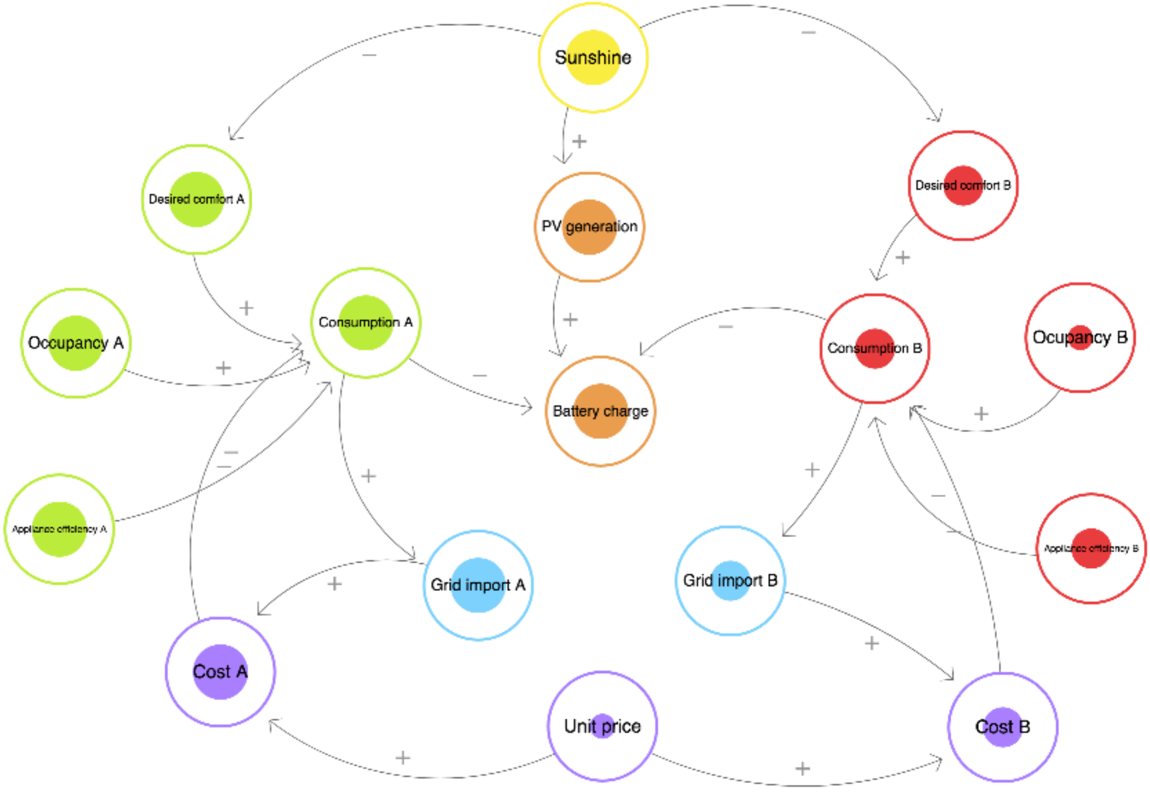


Figure 9 – Bristol Pilot's TwinERGY testbed System Archetype, developed as a CLD model of participant households.

The TwinERGY logic is represented via the existence of the balancing loop between Consumption <--> Grid import <--> Cost, which causes the testbed to ensure that measures are taken when appropriate (e.g., shifting demand, switching appliances off etc.).

This simple archetype can then be used as a building block to model a series of more complex scenarios, e.g., the occasion where energy assets are shared between dwellings (Figure 10), or the peer-transactive operation of a local community energy scheme (Figure 11). The potential combinations are numerous allowing us e.g., to model the scenario where *N* households form a community but unlike Figure 10 do not share energy assets, may be on different tariffs etc. We will not provide the entire range of such variations here, and they can be further developed in support of use cases when the latter are realised in our testbeds with the delivery of Modules.

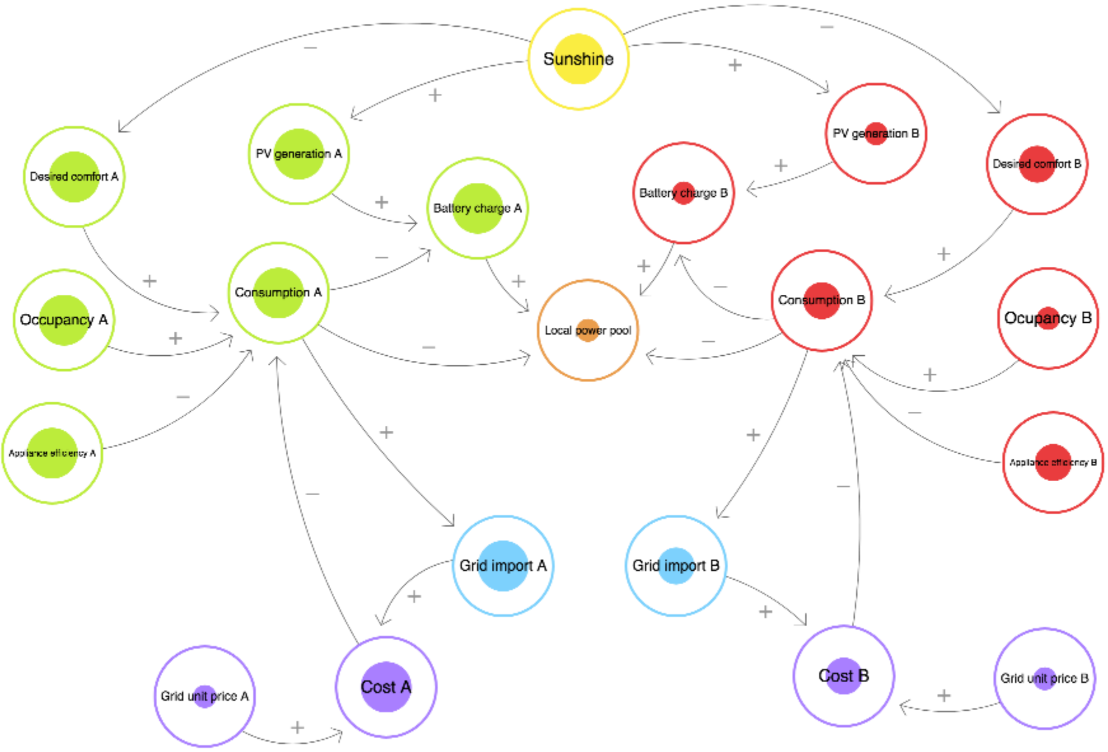


CLD model for shared energy assets
(PV/battery) between dwellings A, B
with demand management active under
(common) variable tariff (winter scenario)

Figure 10 – A CLD model of a testbed comprising dwellings sharing energy assets. Each individual household is an archetype joint effectively via the local testbed.

In Figure 11 the red and green households can exchange energy via access to a local energy 'pool', which enable transactions and are charged from locally generated surplus. In this model we have represented the return as imported energy cost reduction (which, when negative, is a net overall profit). Each household is potentially on a different variable tariff in this instance, hence the separate inputs for Grid-imported energy unit price *A* and *B*.

Having developed the basic archetype, other model instances are easy to be considered and may include a community of an arbitrary number of *N* households joining up in a virtual power plant transacting with the Grid, communities transacting between them and the Grid etc. We will continue identifying such scenarios and capturing them in simple CLD models through the project.



CLD model for peer-transacting energy between dwellings A, B with demand management active under (individual) variable tariffs (winter scenario)

Figure 11 – Local transactive energy scenario between individual households with independent assets.

The models have been developed with the online CLD tool LOOPY[4], because the platform allows for sharing of a web canvas during a collaborative online session. Participants are able to see and share the models and to contribute to their development. LOOPY is also ideal to provide qualitative understanding of the effected behaviour of the modelled system, as it can run elementary simulations based on rough estimates of initial values for inputs (expressed as ballpark graphical 'quantities'). The visualisations include colour and movement and are therefore engaging for participants to understand, without burdening them with formalities of more formal simulation platforms.

These simple but powerful CLD models have been initially developed and sanity-checked with the contribution of Bristol local partners and selected participants. With the

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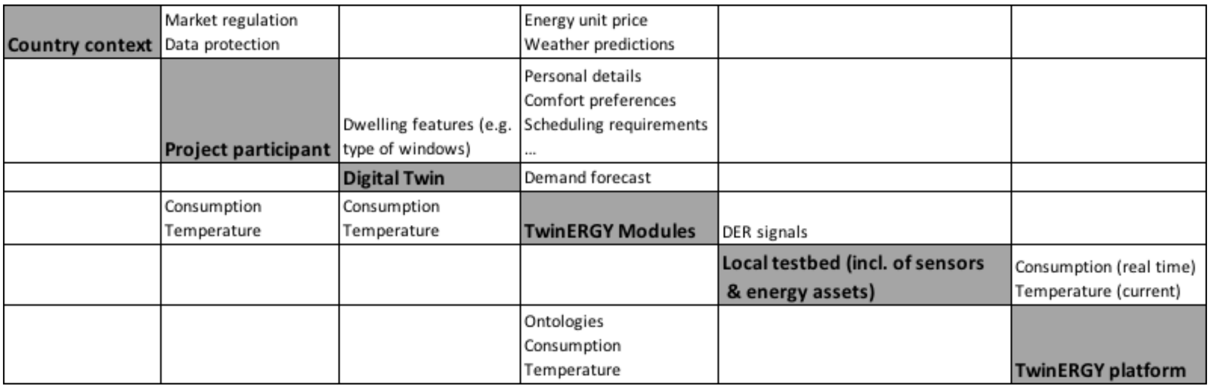
[4] https://ncase.me/loopy/v1.1/

completion of the testbed deployment phase and upon generation of operational data from the relevant system components (PV inverter, battery, smart plugs) on the TwinERGY platform, the models will be further turned into stocks-and-flows in the Vensim modelling tool (see more detail in deliverable D4.3, Methodological Framework p. 53). This will give us the ability to run more accurate simulations based on the real life data.

3.2 Considering interdependencies at local testbed level with N-Sq. charts

In tandem with the development of CLDs that capture interactions from a process perspective, our approach utilises N-square charts to complement these with an informational view of interdependencies, as illustrated in Figure 12 below. Using the technique as described previously in section 2, we identify the essential subsystems and the key information that they exchange. In this way, everything that exist on the same row is essentially an output of the corresponding subsystem, whilst everything on the same column is an input.

In the following matrix we have captured these interactions with the configuration of the pilot in Bristol as a basic model, but at high level it applies similarly across all other demonstration sites. N-square charts give us the ability to identify critical components, especially where heavy interactions and exchanges occur. As such, we can see below that the Modules play a key role in delivering the desired impact, as they practically interface with all other subsystems of TwinERGY.



Country context	Market regulation Data protection		Energy unit price Weather predictions		
	Project participant	Dwelling features (e.g. type of windows)	Personal details Comfort preferences Scheduling requirements …		
		Digital Twin	Demand forecast		
	Consumption Temperature	Consumption Temperature	**TwinERGY Modules**	DER signals	
				Local testbed (incl. of sensors & energy assets)	Consumption (real time) Temperature (current)
			Ontologies Consumption Temperature		**TwinERGY platform**

Figure 12 – Early identification of high-level informational interactions and dependencies across subsystems. A more elaborated instance can be found in the appendix.

Such information exchanges may refer to volatile information (e.g., real-time readings of energy consumption) or more permanent features (e.g., catalogues of energy assets used and their specs). Broad groups have been identified as such within the accompanying spreadsheet matrix model.

3.3 Further actions planned to include Systems Modelling

As the models will be turned into simulations based on real data when available, we intend to utilise them further past the duration of T6.1 and through the project. The below suggestion for engagement activities is intended to bring together more key stakeholders to develop jointly scenarios and derive insights around these models. We envisage that these events could take place mostly in person, as part of future dissemination and exploitation activities, in collaboration with local partners. On-line contingency has been considered and the consortium has the expertise to run and support fully on-line events in case this is deemed necessary.

Table 2: A programme of stakeholder engagement for group exploration, and shared understanding development and collaborative model building.

Event	**When**	**Audience**	**Objectives**	**Consider (inputs)**	**Outcome**	**Key Outputs**	**Impact Level**
Partner meeting	Upon end of D6.1	Project partners	Interdependencies confirmation	System Architecture	Any viability concerns reviewed and addressed	Academic publication	Local
Consumer focussed workshop (PETRA 22[5])	~M19	Academia/ R&D	Understanding of where value is created for stakeholders	Barriers and enablers	Local impact evaluation Understanding scale up implications	User fact sheets Case studies/Value cases	International
Sector focussed workshop (e.g., with BRIDGE partners or SWIP)	~M24	Industry s/h	Preparing the market	Outputs from previous events	Support for business models evaluation	Technology roadmap Potential patents	National and International
Municipalities focussed workshop	~M34	Pilot city authorities' reps	Exploring public value	Pilot results Business models	Policy support	Policy recommendations (e.g., for social housing, public buildings)	Local and National

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[5] Accepted workshop proposal at PETRA '22, Greece: http://www.petrae.org/workshops/EnPESES.html

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4 Conclusions

The role of this companion report was to introduce the reader to *Systems Thinking* and its related modelling practices that are utilised in the context of TwinERGY to model aspects of future energy systems, energy behaviours and anticipated impacts of our interventions. These techniques have been and will continue to be used in a collaborative setting through-life of the project, to allow project partners, participants and industry stakeholders to come together and develop a common understanding of related issues via group model building practices, employed as described in this report.

We adopt Causal Loop Diagrams, used through semi-structured interventions, such as workshops and 'action' case studies, i.e., impromptu experimentation with volunteering participants, planned under the general principles of the Soft Systems Methodology approach. CLDs offer an engaging way not only to partners but also to our project participants to contribute to scenario building with regards to the use of TwinERGY innovations, as experienced through the local testbeds and Modules. The engaging graphical output of online tools like LOOPY allows for developing deeper insights and understanding.

We also employ the technique of N-Square charting analysis, in order to understand better the interdependencies of subsystems, especially from an informational exchange perspective. By developing an initial N-Square diagram reflecting on Bristol's local testbed and applicable use-cases, the pivotal role of Modules in the project becomes clear, even across demonstrator sites. Indeed, a high-level instance of this model captures at broad scale interactions applicable to all pilots.

We will also consider future use of the Multi-Level Perspective approach for evaluation of impact of key outcomes and whether these could shape market paths (e.g., as impactful innovation does in Figure 13 in the appendix). In addition, we will further investigate the use of the Viable System Model, as also described in the appendix, for a more elaborate 'un-packaging' of the subsystems featuring along N-Square chart in a way that would allow interdependencies at lower levels to become clearer when the pilot set ups are fully operational.

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Appendix

Other relevant Systems Approaches

Multi-Level Perspective (MLP)

The Multi-Level Perspective (MLP), as described by Geels and Schot (2007) and shown in Figure 13, is a three-layered framework that is large enough to represent both the SoI and its exogenous environment. Within this model, the demand-side system can be seen as a 'sociotechnical regime' that lives within the environment of the exogenous 'sociotechnical landscape'. This sociotechnical landscape is equivalent to the operating environment as shown earlier in Figure 1 in the main body of this document. The regime is equivalent to the SoI we have already defined. It represents the fixed structure of the system, with technology development trajectories set in a pattern and only incremental changes to technology pursued, as opposed to fundamental ones. Thus, equipment manufacturers may build more efficient versions of their energy-using products, but they will not think of new ways to achieve the desired end-user service.

On the third level are niche innovations. Niche innovators will find new ways to meet a service need, rather than making incremental changes to existing ideas. From time to time these niche innovations can penetrate the established regime; however certain conditions are required, such as the need for the established regime to change due to downward pressures coming from disruptions in the landscape, and the suitability of new technologies to meet that need.

MLP goes much further than a simple systems diagram in that it can help to reveal how systems transform over time. Its applicability to the energy demand system is confirmed by Geels when he states that 'climate change may in future decades become such a disruptive landscape change, triggering such a sequence of transition paths in transport and energy regimes'. This high-level approach could help to answer questions about the underlying and sometimes hidden drivers of energy demand, which have so far been difficult to identify. Wilhite et al. argue that demand is manufactured and is primarily a social construct. They call for new research that approaches the dynamics of energy demand as an understanding of 'sociotechnical change and the co-evolution of infrastructures, devices, routines and habits.' (Whilhite et al., 2000).

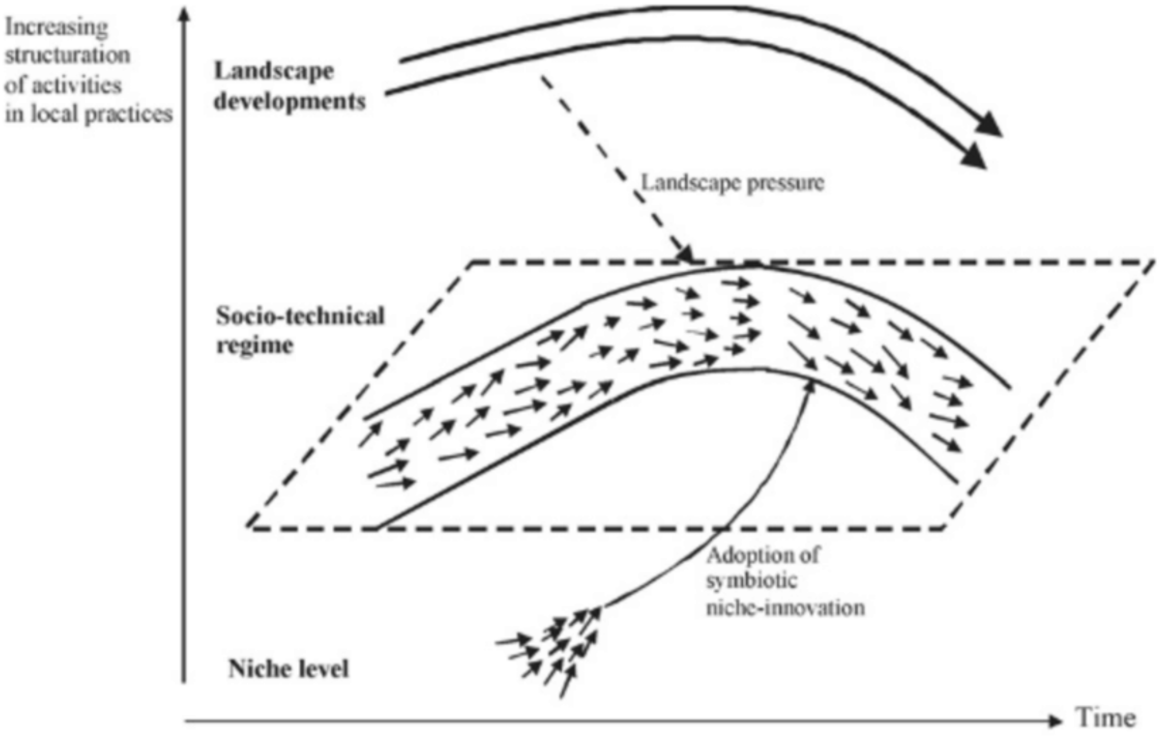

Figure 13 – Transformation pathway of the MLP. Source: Geels & Schot (2007, p. 407)

This emphasis on sociotechnical change chimes well with the MLP and its ability to model how transitions happen within sociotechnical regimes. Specifically, the MLP could be used to gain insight into the effects of overlying and long-term social, political, technical, or macro-economic influences on the demand in the energy system as a whole. An application of the combination of these frameworks for the design of a school has been described in more detail in a relevant case study (Freeman & Tryfonas, 2011).

Viable System Model (VSM)

In this section we provide background information relevant to the Viable System Model and its application to the energy domain. The Viable System Model was originally designed by Stafford Beer to model the viability of an organisation (Beer, 1981; 1985; 1994). Beer studied the human organism and constructed an organisational model for enterprises based on the methods used by the central and autonomic nervous systems to manage the operations of the organs and muscles. The model divides the organisation into three fundamental parts, i.e., Management, Operations and the Environment. The Operations part entails all the operations that take place inside the organisation while the management part controls the smooth operation of the system, ensures its stability,

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facilitates its adaptation to the future trends and structures the policies of the organisation. The environment entails all external entities that exchange data with the system. A general view of the model is shown in Figure 14. Beer suggests that we should model an organisation in the way the human body works, in a way that is not so strict and solid as the pyramid but flexible to adapt to changes caused by the environment.

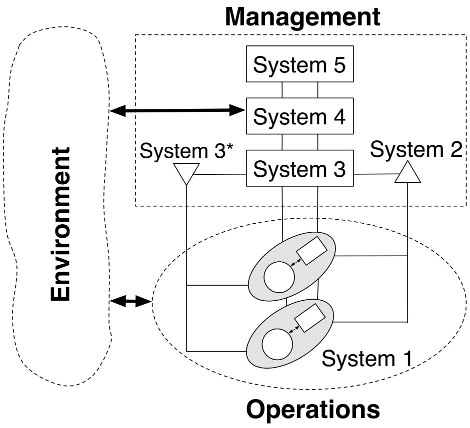

Figure 14 - The Viable System Model

As seen in Figure 14 VSM is composed of six different systems each one of a distinct role.

System 1: Operational units within the organisation. System 1 refers to the operational units within the enterprise. Each unit can communicate with other operational units and the external environment, transferring and receiving data. The overall coordination of System 1's operations is managed through System 2. The control of System 1 is carried out by System 3, while System 3* is responsible for auditing the operations in System 1. Each operational unit within System 1 has its own management system, exchanging data with it and forming a new VSM inside the initial VSM.

System 2: Attenuation of oscillations and coordination of activities via information and communication. System 2 is responsible for the coordination of the activities of the operational units that form System 1. It also communicates with System 3 in order to transfer the results of its coordination actions.

System 3: Management of the primary units. Provision of synergies. System 3 manages the units of System 1, controlling their behaviour by having access to all of them. It is also responsible for the provision of synergies among the operational units. It receives the coordination-related data from System 2 and the results of the audit conducted by System 3* in order to take new decisions regarding the management of System 1. It also communicates with System 4, which dictates the changes that should be made due to the ever-changing external environment.

System 3*: Investigation and validation of information flowing between Systems 1-3 and 1-2-3 via auditing/ monitoring activities. System 3* audits the operational units of System 1 in order to identify whether System 3's management commands are followed by the operational units and whether changes should be made for the System 1's performance improvement.

System 4: Management of the development of the organisation; dealing with the future and with the overall external environment. System 4 communicates with the environment in order to identify changes in it and propose certain approaches to System 5 for the whole system's evolution. It also communicates System 5's decisions to System 3.

System 5: Balancing present and future as well as internal and external perspectives; ascertaining the identity of the organisation and its role in its environment; embodiment of supreme values, norms and rules of the system. System 5 is the upper level of the management part of the VSM. It deals with the policies of the enterprise and its role within the environment. It communicates with System 4 in order to receive information regarding the changes in the environment. After deciding the changes that have to take place in the operational part of the enterprise, it delivers them to System 4. System 5 also monitors the homeostasis between System 4 and System 3 and receives information from System 3 regarding the current status of the system. Ultimately, System 5 is the one responsible for the long-term decisions.

Each operation in System 1 can communicate with the rest of the operations of System 1 and the external environment for exchange data. Their overall function is coordinated by System 2 and controlled by System 3 which is also responsible for the provision of synergies. System 3* is responsible to conduct audits upon System 1 to check if System 3's directions and commands are implemented properly and address the existence of any issues to System 3. System 4 communicates with the external environment so that it can deal with the future trends and identify the various changes that take place in the external environment. It is in contact with System 3 in order to deliver the changes that have to be done and with System 5 which forms the upper level of management that deals with the system's policies and role inside the environment. System 5 is connected with System 3 since it monitors the homoeostasis between System 4 and System 3. Furthermore, System 5 has the responsibility to deliver the ethos of the organisation and take long term decisions that will be passed to System 3 in order to direct System 1 on how to implement them. Also, System 5 has to know the current state of the Organisation, through reports from System 3, in order to take a long-term decision. An interesting characteristic of the VSM is its recursive nature. Each operation in System 1 forms a VSM subsystem with its own operational and management parts.

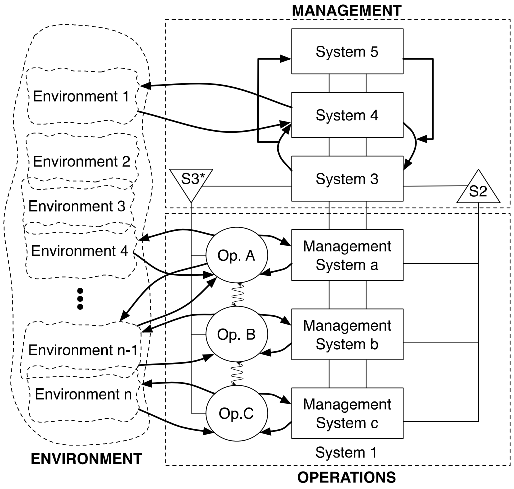

Figure 15 - Multiple environments and operational contexts.

Figure 15 gives a more elaborate view of operations and the environment and offers an insight into how the TwinERGY could be modelled as a VSM, recognising the multitude of entities that exist across pilots, modules and platform features. As discussed, the VSM is also self-referential in a way that each component could be viewed as a VSM in itself.

There are few examples of using the VSM for modelling energy systems in the literature, e.g. (Kouloura et al., 2009; Kouloura 2012). In the following example we will use it to define the model of a (commercial) building with respect to its energy assets and their management.

Example: Modelling Complex Building Energy Assets as a Viable System

The energy management system within a building is the main engine that drives for environmental sustainability. It aims to deliver a reduced environmental footprint through gathering and responding to data that is collected by a thorough network of sensors throughout the building. Typically, there are four main subsystems that exist within the energy management system: HVAC (Heating, Ventilation and Air-Conditioning), lighting, electrical load shedding, and cogeneration of electricity and heat. Tang et al. (2013) suggest that there are two fundamental methods that should be combined to improve energy usage efficiency: reducing the level or energy consumption and shifting consumption to smooth the demand curve.

Perhaps the most complex system that occurs within a smart building is the HVAC system. Despite being so complex, it has a simple main objective: to maximise comfort of the occupants in a building, at minimal environmental and economic cost. A standard HVAC system regulates conditions on a building-wide scale, using a sparse network of thermometers that may not fully represent the area. For example, if there is a thermometer near a heating or ventilation vent then the data gained from that thermometer may not be representative of the whole area, and therefore the data used to adjust the HVAC system in that area would not create optimum conditions. A smart HVAC system will include a large number of sensors that will be able to collect data that can be used to profile conditions throughout the area, and therefore highlight in which areas the conditions need to be altered. The meters that assess conditions measure not only temperature, but also relative humidity and CO_2 content. It is important that all three of these factors are measured, as without the ability to set these factors to an appropriate level, they will have a negative effect on the occupants (Clements-Croome, 2013). These factors are important as it has been proven that "the physical environment can enhance an individual's work" whereas, "an unsatisfactory environment can hinder work output" (ibid.). Furthermore, the internal climate of a building plays a massive role in the health of the occupants of that building. Fisk (1999) studied the effect that illness had on the US economy, due to missing days of work. He found that the total cost of respiratory infections to the US economy amounted to $70 billion. He then estimated that a reduction of up to 50% of sick building syndrome (SBS) symptoms could save up to $38 billions off this figure. The management of air quality in a building is the most effective way of reducing the spread of sick building syndrome, and therefore the HVAC system of the building should be able to manage this effectively. If correctly managed, this could therefore increase the economic sustainability of the building, whilst the smart HVAC system will also increase the environmental sustainability of the building through energy management.

The lighting system proposed improves upon the widely used system whereby the lights are only switched on if there is movement detected. It has been suggested that an energy usage saving of up to 38% could be achieved if a combined lighting strategy is used (Williams et al, 2012). This combined methodology includes using occupancy data, automated daylight adjustment, personal tuning, and institutional tuning (ibid.). Occupancy is the system that the majority of commercial buildings already use, however the system could become more efficient if the area that is controlled by each sensor is smaller. This would mean more sensors, but the presence sensor data could be taken from the same sensors that are used in the HVAC system, access management system, intruder detection system etc. By making the controlled areas smaller, the lighting system will be able to be more efficient in running, limiting the energy wasted on lighting an uninhabited area. The automated daylight adjustment component of the lighting system is more complex, as it requires a constant stream of data regarding the level of sunlight that is entering the building (Williams et al, 2012). This is so that the artificial lights can balance with the level of natural lighting to ensure that a constant lighting condition is achieved. This prevents the system using too much energy by artificially lighting the building when there is a sufficient amount of natural light entering the building through the windows. The smart lighting system may also include automatic blinds, which use sensors to assess if there is too much direct sunlight entering the building.

The ability to choose which energy using systems within a building are to run when the cost of energy is changed is also crucial in reducing energy usage within a smart building. The concept of electrical load shedding relies on the assumption of a smart grid being in operation, with smart meters that can somewhat predict when peak prices of energy are going to occur. This prediction of an increase in energy prices allows for some systems to 'prepare', meaning that they change their output to the maximum or minimum within a set range such that during the time that the system is not active their output remains acceptable. An example of this is The Mirage in Las Vegas, which lowers the temperature of chilled water that is used throughout the building hours before the peak energy price means that the system is temporarily shut down (Siemens, 2012). This means that during the time that the system is turned off the temperature of the water, although it increases, stays within a tolerable range (ibid.). This system requires the categorisation of the various systems that occur in the building into brackets ranging from non-essential to critical, so that they can be treated appropriately in the load shedding system (ibid.).

A further advantage to load shedding systems being installed in energy intensive commercial buildings that occurs on the city-wide level is the effect that they have on the smart grid. Due to the large commercial buildings reducing their energy consumption at peak hours, the energy demand curve that is required of the smart grid is smoothed. The main advantage to this is that the efficiency of the smart grid will be increased massively. Particularly as the shift towards renewable sources of energy becomes more prevalent, having energy consumption that is predictable and as uniform as possible is very important. The current grid in the UK requires inefficient and polluting coal and gas power stations to be on standby to supply energy in the times of peak demand, but if the demand was predictable the potential for supplying all of the energy needed via renewable sources is much greater (Pettitt, 2011).

Although load shedding systems are sure to reduce energy consumption and smooth the demand curve of energy from the smart grid, there are still issues to be resolved regarding the implementation of such a system (Nguyen & Aiello, 2012). Investigation into each individual building and the potential savings which such a system could provide are needed before installation, to evaluate whether the benefits of the system are worth the upfront capital investment.

The cogeneration of electricity and heat has the potential to reduce overall energy usage within a smart building. Within the system, electricity is generated and the excess heat that is given off is transported to the HVAC system, where it can be used to lower the amount of air having to be heated there. The full system is shown in Figure 16 from (Dawes, 2016) – originally developed by Vandewalle and D'haeseleer (2013).

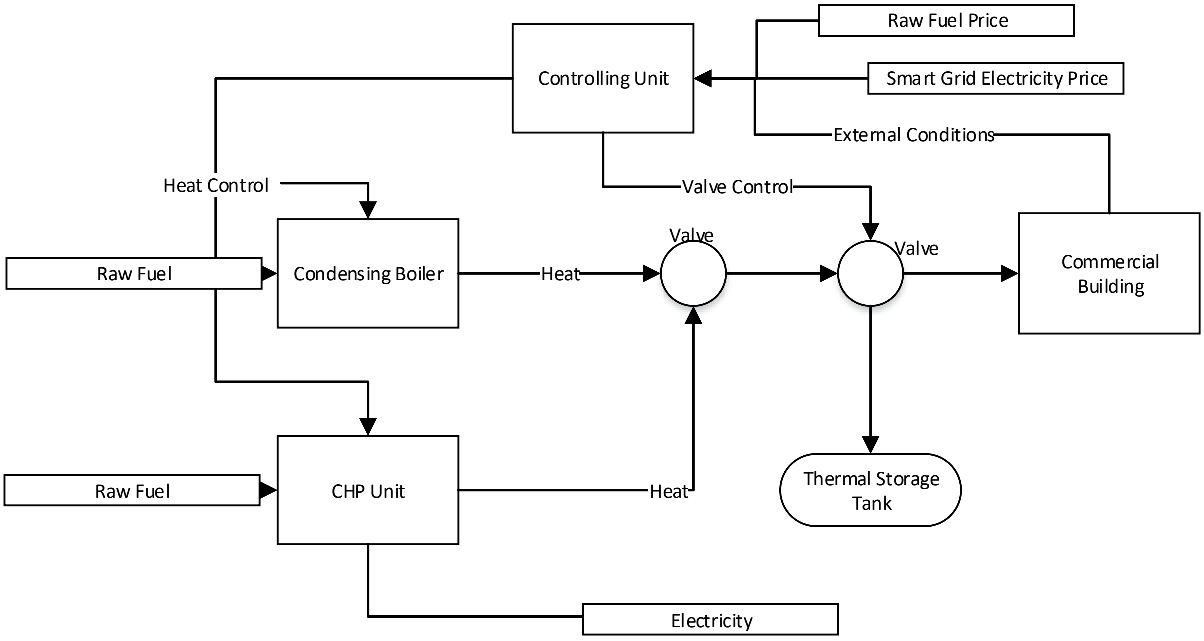

Figure 16 - Heat production building energy system with cogeneration adapted from Vandewalle and D'haeseleer (2013).

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The key component of this system is the controlling unit. This is because the management of the system is based on real time external information, which is fed into this unit, and therefore it is the response of this unit that dictates the effectiveness of the whole system. The comparison between the current cost of raw fuel and the current cost of electricity from the smart grid allows for the controlling unit to determine the most economically optimal approach to sourcing energy (Vandewalle and D'haeseleer, 2013). If the cost of producing both electricity and heat via the CHP (Combined heat and power) unit is lower than the cost of using smart grid electricity needed to supply the HVAC system and the other electrical requirements, then the controlling unit switches the building over to the cogeneration unit. This situation is most likely to occur at peak hours, when the cost of smart grid electricity is going to be at a maximum. Therefore, it can be seen that this system has two main advantages: a reduction in the energy expenditure of the building, and a reduction in demand on the smart grid at peak times. The latter of these advantages has the knock-on effect of smoothing the demand curve on the smart grid, and therefore making it more efficient.

The various energy assets that are present in this scenario can be modelled using the Viable Systems Model (VSM). The VSM is a good fit to use to represent this system as it 'reinvents' itself at each level (Espejo and Gill, 2002). This is to say that each individual subsystem can be thought of as if it contains a full size VSM within it, as illustrated below in Figure 17.

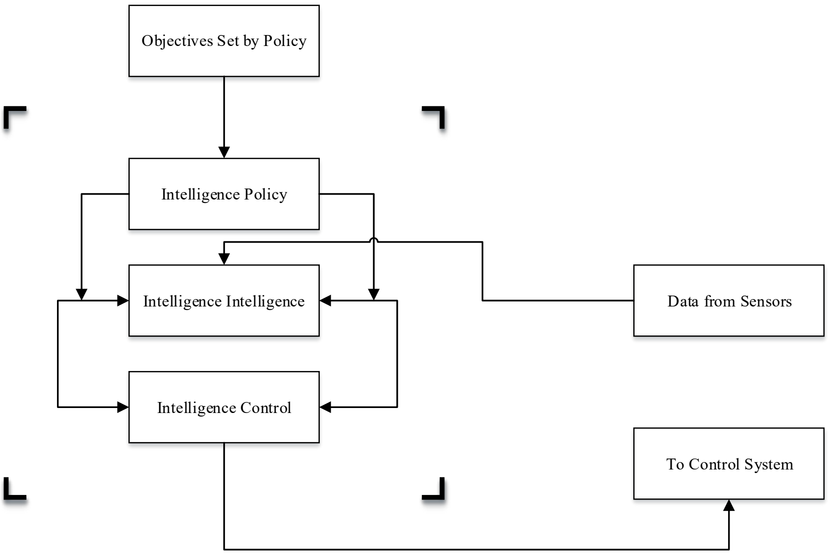


Figure 17 - An expanded view of the Top Level Intelligence System.

The Policy section of the Intelligence block (Second Level) has the responsibility of translating the objectives set by the main Policy block (Top Level) into factors that can be compared against the data that is passed into the system from the sensors. For example, within the energy management system is the HVAC subsystem. As previously identified the HVAC system has the objective, set by the Top Level Policy system, to provide optimum working conditions at the lowest environmental and economic cost. However, it acts upon data received regarding the temperature, moisture content and CO2 levels, and so it is the responsibility of the Second Level Policy system to translate the objectives into values that can be used to judge what adjustments need to be made in the system, based upon a comparison with the data obtained via sensors.

Furthermore, the VSM is useful to consider as it explicitly states the need for an interaction with the environment, as opposed to being self-regulating on purely the component level. This is crucial as it allows for constant feedback on external conditions, allowing for constant adjustments to be made. This ensures that conditions within the building are kept at the optimum level throughout the day. This constant level of feedback also means that short term changes can be made in the system. For example, the lighting system should be able to adjust for a short-term change in the level of natural light that enters a building. This requires the constant monitoring of natural light, so that if it drops the level of artificial light provided can be suitably adjusted in order to maintain a constant lighting level (Dawes, 2016).

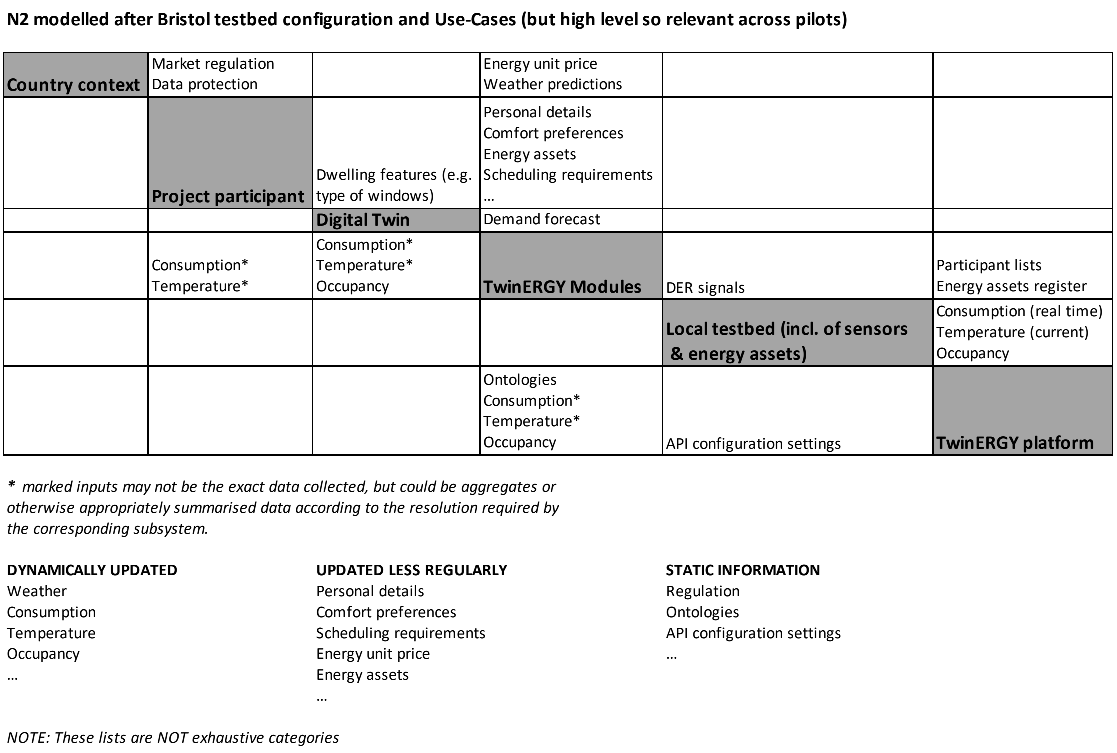
The model suggested is heavily reliant on the compatibility of each of the components and systems. This has, historically, been a source of frustration when trying to integrate building automation and control systems on a building wide scale (Fisher, 1999). Previous solutions have been suggested to fix this issue, such as setting a National Standard to use BACnet, however these standards are only enforced in new buildings, and so there is still much difficulty in retrofitting compatibility across whole buildings (ibid.). The solution suggested for the VSM is the Co-ordination system. It is the sole responsibility of this system to manage the interface between the building management system, represented by the meta-level organizational block, and the components, represented by the Implementation block. If the whole system is to be achieved, it is crucial that the Co-ordination block is efficient at translating these commands. Co-ordination is also needed to ensure that the commands issued by the meta-level organizational block reach the specific components within the Implementation block (Dawes, 2016). The responsibilities of each subsystem are shown in more detail in Table 3.

Table 3: A mapping of the VSM to building energy management systems capabilities (Dawes, 2016)

	Sub-System	General Responsibility	Responsibility within a Smart Building
Meta-Level Organizational Unit	Policy	• To understand and implement the objectives of the whole system. • Provides an overall level of guidance that will ultimately shape the performance and direction of the whole system.	• Sets the primary objective of the system as providing maximum comfort for minimum economic and environmental cost. • Retains the ability to change the objectives of the system, if the user needs to change them.
	Intelligence	• Compares the feedback gained from sensors in the building and makes appropriate changes so that the objectives set by the 'Policy' sub-system are met.	• Gains feedback from the environment through the network of sensors and compares the performance of the whole system against the objectives set by the 'Policy'. • Makes appropriate changes if the environment conditions are not as specified by 'Policy'.
	Control	• The channel through which the data collected by sensors throughout the building is passed. • Instructions that are issued by the 'Policy' and 'Intelligence' sub-systems are passed onto the components in the 'Implementation' sub-system.	• Passes instructions which are issued by 'Intelligence' that are based on the comparison between external conditions and the objectives set by 'Policy'.
	Co-ordination	• Responsible for managing the interface between the Organizational Unit and the physical components in the system. • Feeds instructions that are sent by 'Control' to the components in 'Implementation'.	• Transfers instructions issued by the Meta-Level Organizational Unit are translated into actions for the components to complete.
	Implementation	• The various systems that are needed to achieve the outcomes that the 'Policy' subsystem identifies.	• Contains the subsystems shown in the Generic System Architecture that are responsible for changing the internal conditions based on the instructions passed from 'Intelligence'.

More elaborated N-Square TwinERGY chart

The version below is a more elaborated instance of the TwinERGY N-Sq., resulting through subsequent iterations of consultation with local pilot partners and review of relevant system architecture and use-case deliverables (D4.4 'System Architecture' and D2.2 'Stakeholders analysis: KPIs, Scenarios and Use Case definition'). The relevant spreadsheet document will be kept up to date through the project and the current instance will be always available to partners via the project documents site.



N2 modelled after Bristol testbed configuration and Use-Cases (but high level so relevant across pilots)

Country context	Market regulation Data protection		Energy unit price Weather predictions		
	Project participant	Dwelling features (e.g. type of windows)	Personal details Comfort preferences Energy assets Scheduling requirements …		
		Digital Twin	Demand forecast		
	Consumption* Temperature*	Consumption* Temperature* Occupancy	**TwinERGY Modules**	DER signals	Participant lists Energy assets register
				Local testbed (incl. of sensors & energy assets)	Consumption (real time) Temperature (current) Occupancy
			Ontologies Consumption* Temperature* Occupancy	API configuration settings	**TwinERGY platform**

** marked inputs may not be the exact data collected, but could be aggregates or otherwise appropriately summarised data according to the resolution required by the corresponding subsystem.*

DYNAMICALLY UPDATED	**UPDATED LESS REGULARLY**	**STATIC INFORMATION**
Weather	Personal details	Regulation
Consumption	Comfort preferences	Ontologies
Temperature	Scheduling requirements	API configuration settings
Occupancy	Energy unit price	…
…	Energy assets	
	…	

NOTE: These lists are NOT exhaustive categories

Figure 18 – a more elaborated instance of N-Square interdependencies mapping.