The Modular Structure of Housing Utilities: Analyzing Architectural Integration Patterns

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***Abstract*—Modularity is considered a powerful concept within many domains. While modular artifacts are believed to have the potential to exhibit several beneficial characteristics such as evolvability, the actual realization of this evolvability or flexibility remains challenging. This paper considers houses as modular structures and employs the combinatorics underlying Normalized Systems Theory, as well as the integration patterns it proposes, to analyze design alternatives for the incorporation of electricity, heating, air conditioning and Internet access utilities within houses. The paper demonstrates that the integration patterns can be applied at several modular granularity levels. An analysis is presented regarding the currently most frequently used integration patterns (as well as their level of application), and those patterns that should deserve additional exploration. The adopted approach to analyze the modular design alternatives for housing utilities is believed to be applicable within other domains as well.**

Keywords–Modularity; Housing; Evolvability; Normalized Systems; Architectural Patterns.

I. INTRODUCTION

Modularity is a powerful concept used in many application domains (including computer science, product engineering, organizational sciences, and so on) and is generally assumed to provide benefits including evolvability. Nevertheless, obtaining such adaptability or evolvability in practice can be challenging. The different modules in a system might be dependent on one another, so that a change in one module might lead to (few or many) changes in other modules. Some of these ripple effects may be due to so-called cross-cutting concerns in the sense that they are required across the whole modular structure (e.g., security in a software application). As a cross-cutting concern is, by definition, present in many modules of a system, it is clear that changes in that regard can easily impact several places within a modular structure (e.g., every data entity should be adapted so that it can securely stored in order to create a more secure overall software application).

Also houses can be considered as modular structures. They exhibit several abstraction levels (e.g., houses consisting of rooms and built by bricks) and could benefit from evolvability (e.g., connecting an additional room to an existing house). Moreover, houses seem to contain several cross-cutting concerns (e.g., water and electricity supply) and subject to ripple effects when undergoing change (e.g., the need to drill into existing walls or even tear down walls in order to be able to provide an additional room with water because the connecting old walls did not provide any connection), hampering their evolvability. This paper extends a previous paper [1] by investigating and illustrating the applicability of modularity reasoning (and in particular the concept of cross-cutting concerns) within the design of housing utilities. We argue that, in general, the utilities within houses can be considered as cross-cutting concerns. Whereas our earlier work focused on the electricity and heating utilities, this paper also analyzes airconditioning and Internet access utilities in a housing context, thereby further supporting our claim of the applicability of our reasoning. We propose design alternatives for housing utilities based on the modular integration patterns for cross-cutting concerns as suggested by the combinatorics underlying Normalized Systems Theory (NST) [2]. The theory is suitable for this purpose as it aims to provide prescriptive guidance on how to design evolvable modular systems.

It is important to mention upfront that none of the authors of this paper are experts within the domain of housing architecture. Therefore, the intention of the paper is not the prescribe in detail how housing architectures should be improved in the future. Rather, we intend to show that it makes sense to apply the modularity reasoning presented within NST (which originated at the software level) to other domains in which modularity plays a prominent role. We will structure this paper as follows. In Section II, we provide a brief overview of related work regarding modularity, NST and evolvable housing. Next, in Section III, we present the set of considered integration patterns for modular structures. We then apply these patterns for the concerns electricity (Section IV), heating (Section V), air conditioning (Section VI) and Internet access (Section VII). Finally, we offer our reflections and conclusions in Sections VIII and IX, respectively.

II. RELATED WORK

In this section, we discuss some areas of related research. We briefly discuss, consecutively, modularity, NST and some earlier work on the evolvable design of houses.

The modularity concept generally refers to the fact that a system is subdivided into a set of subsystems. Modular artifacts are deemed interesting due to several potential benefits that are attributed to it. For instance, designing a system in a modular way is expected to lower the complexity as the design can be decomposed into a set of smaller (less complex) problems [3]. Also, once a module has been well designed and tested, it can be reused in other systems without significant additional costs. Another major benefit expected from modularity is increased flexibility or evolvability. In a modular artifact, one particular part (module) of the system can be substituted for another version of it, without the need to build up the artifact again from scratch. This type of plug-and-play behavior allows for variation (using the same set of available module versions, different aggregations or variants can be realized) and evolvability (over time, an artifact can evolve from one variant to another) and has been considered as the "power" of modularity [4].

The realization of a good modular design in practice, enabling the mentioned advantages like evolvability, is very challenging. It is generally accepted that the coupling (dependencies and interactions) between the modules in a system should be studied and minimized [3][5][4]. However, how this should be attained is unclear and few theoretically underpinned and generally accepted practical implications are available in literature. One approach which aims to provide a theoretically founded framework with practical implications, is NST. The origins of NST are situated in the formulation of a set of design theorems for the creation of evolvable software systems. Here, evolvability is operationalized by demanding Bounded Input Bound Output (BIBO) stability on ever growing systems. The theory proves that the isolation of all change drivers in separate constructs (Separation of Concerns), the stateful calling of processing functions (Separation of States) and the ability to update data structures or processing functions without impacting other data structures or processing functions (Version Transparency) are necessary conditions in order to obtain stability [6]. It has been shown that these theorems can actually be formulated in more general terms for modular systems [7] and seem to appeal to the basic combinatorics regarding modularity [2]. More specifically, the promise of modularity is that maintaining a particular amount of versions of modular building blocks will result in an exponential amount of available system variants. However, in case a modular system is not well designed (e.g., by not adhering to the theorems), a change in one particular version of one particular module may have an impact (ripple effects) on other (versions of) modules. This number of impacts will typically grow (in an exponential way) with the size of the system and its dependencies.

Adhering to the NST design theorems is difficult as they demand a very strict and fine-grained design of a system, and every violation will result in a limitation of the evolvability of the system. Experience with respect to the realization of such systems has shown that such design becomes much more realistic in case a set of design patterns (so-called "elements") are employed [2]. Each individual element is a generic modular structure for a basic functionality for the type of system at hand and can be parametrized (and if necessary, customized) over and over again when an actual system is built. For instance, in the case of software systems, a general structure for data, task, flow, connector and trigger elements was provided [2]. Stated otherwise, the set of modules constituting an element becomes a reusable module at a higher abstraction (or granularity) level. In essence, each element provides a core functionality (e.g., representing data) as well as an incorporated integration with the relevant cross-cutting concerns in the domain (e.g., security and persistency for data). In order to maximize the envisioned evolvability, it is important that these cross-cutting concerns are integrated at the most fine-grained level possible (such as these elements) and that the parts in the elements connecting or dealing with the cross-cutting concerns are properly separated in distinct modules that are version transparent.

As we stated above that houses can be considered as modular systems and contain cross-cutting concerns, NST seems to be applicable in this domain. To the best of our knowledge, little previous work exists on the evolvable modular design of houses. Some interesting exceptions do however exist. In terms of academic research for instance, Keymer [8] lists and discusses a set of design strategies for increasing the possibilities of buildings to accommodate change, some of them pointing to relevant cross-cutting concerns in this respect (i.e., several ways of distributing services such as heating, ventilation, electrical wiring, plumbing, etcetera). Or, when considering real-life projects, the Hivehaus "modular living space" project [9] can be considered as an interesting effort in dealing with the design of houses in a modular way while taking care of the proper integration of cross-cutting concerns (see Section VIII). Therefore, the use of underlying theory such as NST (and the integration patterns following from this, as discussed in Section III) to analyze the modular design of houses in a more systematic way is in our view an interesting extension of existing work. Whereas our earlier publication [1] focused on the electricity and heating utilities, we now also conduct a similar analysis to airconditioning and Internet access utilities.

III. PATTERNS FOR CROSS-CUTTING CONCERN INTEGRATION

Based on NST and the implications of its theorems [2], we differentiate between the following integration patterns of cross-cutting concerns. As a first category of integration patterns, we consider cross-cutting concern modules added to the main modules wherein each of the cross-cutting concern modules handles the full functionality of that cross-cutting concern itself. We call this the *embedded integration pattern* and refer to it as *configuration 1*. This embedded module can be dedicated (in case the module was customly designed for the system at hand) or standardized (in case a standardized module is employed to handle the concern). We refer to the first variant as *configuration 1A* and the second one as *configuration 1B*. For modules in the context of a software system, think of a separate module added to a data entity taking care of the persistency of that data entity in a custom designed way (1A) or by using a standard module (1B) for this purpose.

As a second category of integration patterns, we consider cross-cutting concern modules added to the main modules wherein the cross-cutting concern modules are merely connections ("relay modules") to a more elaborate (external) implementation framework of the cross-cutting concern that is actually performing the needed functionality. We call this the *relay integration pattern* and refer to it as *configuration 2*. Such relay modules can connect to a dedicated framework (in case the framework was customly designed for the system at hand) or standardized framework (in case the framework is standardized and, for instance, publicly available). We refer to the first variant as *configuration 2A* and the second one as *configuration 2B*. For modules in the context of a software system, think of a separate module added to a data entity serving as a proxy to a persistency framework, which was specifically designed for its own system (2A), or to an available standard solution such as JPA (2B). Finally, we mention the option to let the relay modules connect to another module (i.e., a *framework gateway*) and in which only this framework gateway directly connects to the external implementation framework. We refer to this third variant as *configuration 2C*. For modules in the context of a software system, think of a dedicated gateway module connecting to the JPA framework but allowing all relay modules to be technologically independent of this framework by calling the gateway in a JPA agnostic way.

IV. ELECTRICITY PATTERNS

In this section, we consider the electricity utility within houses as a cross-cutting concern. We consider the integration architectures as proposed in Section II at the modular granularity level of a city or community, house, room and device. Afterwards, we consider some advanced issues and reflections.

A. *City or community level*

Most cities and communities of developed countries need electricity, so it can be considered as a cross-cutting concern. Here, we consider how a city or community can power its electrical grid as a whole (the distribution of electricity to individual buildings is discussed later on).

A first option could be to have all cities/communities have there own electricity generation (configuration 1). In primitive communities, custom built solutions might be considered (1A), but typically the use of standard solutions (1B) would be more realistic (e.g., the reproduction of a typical power plant by means of nuclear reactions, coal, etc.). However, this often lacks economies of scale (it is more efficient to have large power plants producing energy for more than 1 city or community) so typically a city's electricity grid is connected to a national electricity grid with one or more electricity plants dividing the electricity over a large set of cities and communities (configuration 2). Each country might create its own specifically designed grid connecting with the multiple cities and communities (2A) or make use of a standardized electrical power distribution network between cities (2B).

While this latter solution is most frequently opted for, it also has some drawbacks in terms of dependencies. For instance, if the central grid goes down, all connected cities and communities are lacking electricity. Therefore, in reality, most electrical grids are divided into several isolated areas avoiding that a problem in a particular part of the grid to get escalated into the complete (national) electricity grid. Moreover, changes in the standardized network still have their impact on the relay modules (which should nevertheless be encapsulated within the cross-cutting concern handling relay module and not be incorporated within the core module itself). Consider for instance a change in the voltage of the network or from alternating current (AC) to direct current (DC). In fact, the limitations (at that time) for distributing DC over long distances (in order to be able to adopt integration pattern 2B), was one of the main reasons for the general prevalence of AC in the so-called "War of the Currents". One could even imagine the situation in which all cities plug their individual grids into a centralized relay module (power supply) tapping into the global electricity grid (2C) and shielding the individual cities and communities from changes in the standardized framework used.

B. *House level*

Within every city, community or electricity grid area, electricity typically has to be available within every house. Therefore, it constitutes a cross-cutting concern at this level as well. Sometimes, individual houses have the possibility to generate their own electricity by using, for instance, a fuel based electricity generator, solar panels, heat pumps, etc. Furthermore, new technological developments have allowed the creation of home based batteries with large storage capacities, even allowing to store electrical power for a whole house for a considerable amount of time. As this provides a significant amount of independence and sometimes offers budget friendly solutions, this integration pattern can be interesting in certain situations. Moreover, a certain amount of flexibility is enabled as each individual house can choose for the most suitable type of energy in their situation (e.g., those areas with a high exposure to sun light might opt for solar panels instead of a wind mill). In that case (except when they want to transmit the overcapacity to the central electricity distribution network), no distribution framework (see previous subsection) is required and the generators and batteries support the modules for the adoption of integration pattern 1 (typically configuration 1B).

Most people, however, do not opt for the duplication of power generators and batteries in each and every individual house and choose for the option of a connection module plugging into the publicly available electrical power distribution network (typically standardized, so configuration 2B). Similar as stated above, dependencies regarding the availability of the distribution network as well as changes in the power distribution network affecting all connection modules of houses, remain possible disadvantages of this integration pattern.

C. *Room level*

Within every house or building, most if not all rooms require electricity in terms of a set of available sockets where individual devices (cfr. infra) can be plugged in. Therefore, it constitutes a cross-cutting concern at this level as well. Based on the integration patterns we summarized in Section III and similar to our reasoning expressed above, it would be theoretically possible for each room in a house to generate the electricity required (configuration 1A if custom designed, configuration 1B if a standard solution is opted for). Nevertheless, individual heat pumps, electricity generators, etc. for individual rooms are —to the best of our knowledge— typically not applied. Therefore, configuration 2 (typically 2B) is applied by having sockets plugging into the grid network of the house. In certain situations, configuration 2C might be relevant as well. For instance, houses employing a combination of electrical sources (tapping from the publicly available grid, as well as producing a portion of energy themselves by solar panels) could benefit from having the possibility of shifting between them (e.g., using the solar energy when electricity is being generated or available on the local battery and the public grid in all other cases). By having the relay modules (sockets) connecting to a gateway switching module (connecting to the solar panels and public grid), only one electricity grid for such house should be created.

D. Device level

Ultimately, electrical power should be made available to individual devices for which it is required in order to work properly. One possibility to obtain this power is by having a built-in generator or battery in a device. While the generator variant hardly exists in practice, batteries within devices are common practice. Such batteries exist in both custom built variants (integration pattern 1A) or by the use of general purpose variants (integration pattern 1B). A configuration like this obviously provides the device a certain degree of autonomy (i.e., the device can operate on its own) and absence of specific dependencies in this respect. For instance, such configuration might be of great importance for devices to be used witin an Internet of Things (IoT) context. However, incorporating batteries in every device might be a significant engineering challenge (sometimes even simply impossible) and requires the duplication of a battery in each device. Therefore, in many cases a centralized configuration will be adopted in which the device is connected to a custom developed (configuration 2A) or, typically, a standardized electrical grid (configuration 2B).

Recall that we noted in Section IV-A that historically, AC was chosen above DC at the level of cities and communities due to (among other things) its possibility to transport electrical current along larger distances. The consequences of this choice ripple down to the lower modularity granularity levels, such as the level of the devices, which then have to deal with electricity delivered at AC. However, most electrical devices need DC to function properly. As stated above, it is the relay module that should encapsulate these kind of dependencies regarding the external framework and ensure conversions for mutual compatibility if required. Therefore, an adapter (typically with a device specific connection) is often included at the level of the cross-cutting connecting module (i.e., between the device and the electrical grid) in order to convert AC (coming in from the plug) to DC at the right voltage (typically also resulting in a certain degree of loss of electrical power, which is converted into heat, depending on the efficiency of the adapter). *This clearly shows the duplication of the AC to DC conversion functionality present within all relay modules (here: adapters).* Moreover, in terms of flexibility and adaptability, this situation nicely illustrates that changes in the external framework (e.g., a conversion of AC to DC within the public electrical grid) would impact all relay modules. In case the AC/DC conversion would not be separated in a distinct module (e.g., the conversion would be performed in the devices themselves instead of via a separately in/unpluggable adapter), the impact would be even more profound as the devices themselves should be adapted. Based on our analysis of the different modular granularity levels, one could argue for the need to investigate the option to have AC/DC conversion happening at the house level instead of the device level. This way, the duplication of adapters for each separate device could be eliminated and the dependence on DC would be avoided. More specifically, such situation would correspond to the cross-cutting concern integration pattern 2C where the main modules are the devices, the sockets are the relay modules (no need for adapters anymore) and the centralized AC/DC converter would fulfill the role of the gateway module. In fact, recent initiatives regarding new possible electricity (micro)grid configurations seem to suggest these type of integration patterns [10].

E. Overview and advanced issues

Table I provides an overview of the granularity-integration pattern combinations for the electricity provisioning of houses. We can observe that, at most modularity levels, a standardized integration pattern (i.e., 1B and 2B) is opted for. This tends to indicate a certain maturity within the respective domain, which is in accordance with our expectations. While dependence on the external framework is an important limitation regarding integration pattern 2B, we remark that an interesting research avenue regarding integration pattern 2C at the device level can be identified. Further, the table illustrates that, when aiming for maximum flexibility, the integration of concerns tends to be solved at more fine-grained levels (going downwards in Table I) and in a more standardized externally enabled way (going to the right in Table I) in the long run.

TABLE I. OVERVIEW OF THE DIFFERENT GRANULARITY-INTEGRATION PATTERN COMBINATIONS REGARDING ELECTRICITY.

	1A	*1B*	*2A*	*2B*	*2C*
city/community				●	
house		●		●	
room				●	●
device	●	●		●	○

●: currently employed, ○: to be explored

Further, the electricity cross-cutting concern might be enriched with additional features for which our proposed granularity levels and integration patterns might prove useful during the analysis of their realization options. Consider for instance on/off switching. Many devices (such as light bulbs) using electricity to function need to be able to switched on (i.e., emit light) and off (i.e., dim the light). Typical approaches consist of a switch attached to the lamp itself (required in case of configuration 1) or a separate switch integrated into the electrical grid of the house itself (the integration structure of the external framework in case of configuration 2). While this approach has worked well for many years it still requires manual intervention at the location of the switch and, in the latter case, requires the reconfiguration and integration of the switches when a lamp would be relocated within the house. During the last decade, attention has grown for more advanced home domotics in which switches can be managed by software (e.g., allowing to automatically switch devices on at a predefined time slot) and in a remote way. Again, this could be done by placing individual sensors/programmable controllers with individual remote controllers (configuration 1B, if standardized equipment is used). Alternatively, a network of sensors/programmable controllers could be used having one central management and remote control (configuration 2B, if standardized equipment is used), which manages all connected switches. This would also allow the use of aggregated actions, such as switching on or off all light bulbs at once at a predefined time slot, and enable parameter reconfiguration in a centralized way. Integration configuration 2C could even be opted for when, for instance, all sensors/programmable controllers connect to one central connection module allowing to be manipulated by means of multiple remote controllers and protocols (e.g., a traditional remote, smartphone, etc.).

V. HEATING PATTERNS

In this section, we consider the heating utility within houses as a cross-cutting concern. We consider the integration architectures as proposed in Section II at the modular granularity level of a city or community, house, room and brick. Afterwards, we consider some advanced issues and reflections.

A. City or community level

As all households need heating, a source of heat should be transported to or be generated within every house. Therefore, it represents a genuine cross-cutting concern within a housing context. In contrast with the electricity concern we discussed in Section IV, it is rather rare and exceptional that heating is generated and provided at the city or community level, which implies that heating is provided at more fine-grained modular levels (cf. infra). Some initiatives at the higher level of the city or community can however be noted. For instance, an initiative in Rotterdam was recently reported [11] in which residual heat from petrochemical companies around its port is recuperated. While it concerns warmed water being generally too cold to be useful for industrial purposes, it might still suffice to provide the heating for (a large amount of) houses. Referring to the case of Rotterdam, it is claimed that heating can be provided for up to 500.000 households in its surrounding area via a so-called heat network by means of pipelines. In terms of the NST integration patterns, this would correspond to integration pattern 1 at the level of Rotterdam's area (and more specifically 1A as it is a first and, by definition, non-standardized implementation of the concern). Clearly, this initiative was inspired by the fact that this allows for efficiency gains as the considered household do not have to produce their own heat in one way or the other: as the heat would otherwise be "lost", it is now recuperated at a very low cost. Therefore, the heat at the level of each house can be tapped from an external network (i.e., integration pattern 2 can be adopted at this level, cf. infra).

B. House level

As stated before, most houses take care of their own heat generation: a house typically has a central heating system meaning that a central heating boiler uses electricity (cfr. supra) or petroleum to generate heat and convert cold into warm water. Another option could be to use heat pumps. This water will then be distributed along the different rooms in the house later on (cfr. infra). Considering the granularity level of a house, this therefore means that typically integration pattern 1 is opted for (and more specifically 1B, as most households use a standardized heat generator for this purpose). This way of working clearly implies certain benefits such as independence from external heat generation providers. However, one might wonder whether this is always the most efficient or environment friendly way of working. As we mentioned in Section V-A, it is interesting to see that certain initiatives are being taken into the exploration of other integration patterns, such as the so-called heat distribution networks. Here, heated water is produced in a central location for multiple houses and then distributed among them. Therefore, integration architecture 2A (as the solution is typically not yet highly standardized) is opted for in this case.

C. Room level

While a garage or cellar might not be in need of explicit heating, most other rooms within a house (such as the living room or bathroom) are. As a consequence, it can be considered as a relevant cross-cutting concern at this level as well. As mentioned before, most houses today employ a central heating system in which heated water is produced at one centralized place in the house and then transported via water pipes to the required rooms in which a heating element/radiator is present. The warm water causes the element to warm up and release its heat into the room, after which the water (which partly cooled down) returns to the central heating system. As these systems and their pipe networks are highly standardized and commonplace, integration architecture 2B is typically applied. This allows an efficient generation of heat but also clearly entails a dependency of all rooms on this central heating system: in case it would fail or be replaced in such way that the old pipe network no long suffices, all rooms would be heavily affected. Using a framework gateway that decouples the pipe network from the boiler might prevent this and would even allow to switch between different sources of heat (electrically generated, via a heat pump or via the external heat distribution network), which would correspond to integration architecture 2C. In case of absence of a central heating system, integration architecture 1 might still be used. For instance, some houses (although a minority) still use systems in which radiators are placed within rooms. These radiations use the plug to tap electricity and generate heat at their own spot (representing configuration 1B). The use of a fireplace corresponds to the same architecture as well (or configuration 1A in case it concerns a custom designed fireplace). And theoretically speaking, one might also think of situations in which each room is equipped with things such as its own heat pump, although such solutions —at this point in time— are very expensive and inefficient.

D. Brick level

Finally, in order to have more homogeneous heat dispersion in rooms, heating elements incorporated in the floor are sometimes adopted. In such design, the heating pipes are traditionally also connected with a central heating boiler, representing integration architecture 2. Nevertheless, such design is typically not really scalable or flexible as changes (for example, extensions of the heating system to other or larger rooms) might require to break up the floor as a whole. In addition, designing standardized solutions might be more difficult as many rooms take on different shapes and sizes. As a purely speculative and thought provoking alternative, we therefore envision the integration of the heating cross-cutting concern at the level of an individual brick as represented in Figure 1 [2]. In every such element, standardized transport pipes would be embedded for the transportation of hot water, nicely fitting onto the pipes of every similar adjoining brick. This would provide a remarkable degree of scalability when compared to traditional floor heating: as different rooms are built or expanded throughout time, additional bricks (with integrated pipes) could be used, enlarging the area that can be heated. Clearly, just as it was the case for the device level for the electricity concern, the brick level seems to represent the most fine-grained modularity level where the heating cross-cutting concern can be meaningfully integrated.

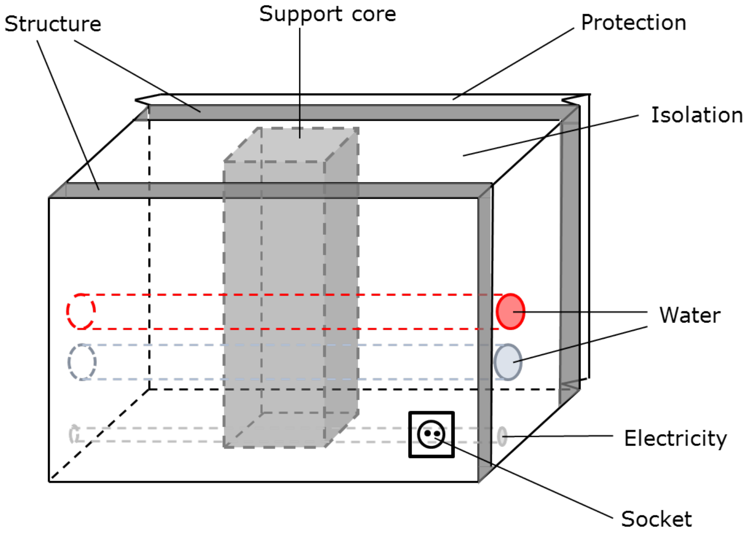

Figure 1. A construction element integration cross-cutting concerns [2].

E. Overview and advanced issues

Table II provides an overview of the granularity-integration pattern combinations for the heating of houses. We can observe that, at most modularity levels, a standardized integration pattern (i.e., 1B and 2B) is opted for. An exception is the integration of heat at the city or community level, which still resides a non-standardized variant (1A), but could easily evolvable towards configuration 1B as it gains maturity. Again, this tends to indicate a certain maturity within the respective domain, which is in accordance with our expectations. As the dependency on the external framework is an important limitation regarding the use of integration pattern 2B, we can identify an interesting research avenue regarding integration pattern 2C at the room level. Additionally, we propose to consider the integration of the cross-cutting concern at an even more fine-grained level (i.e., a brick) in the future. Further, the table illustrates that, when aiming for maximum flexibility, the integration of concerns tends to be solved at more fine-grained levels in a more standardized externally enabled way (stated otherwise: evolving towards the right lower corner in Table II).

TABLE II. OVERVIEW OF THE DIFFERENT GRANULARITY-INTEGRATION PATTERN COMBINATIONS REGARDING HEATING.

	1A	*1B*	*2A*	*2B*	*2C*
city/community	●				
house		●	●		
room		●		●	○
brick				○	

●: currently employed, ○: to be explored

Further, it should be clear that the heating cross-cutting concern is highly related to the preservation of heat by, for example, insulation. Also here, the same modular aggregation levels might be relevant: the house (e.g., an isolating roof), the room (e.g., a well-closing door or insulation being put behind a wall) and the brick (e.g., insulation incorporated in every individual brick). And similar to the on/off switching of electricity consuming devices, heat distribution throughout a house might benefit from more specific, remote and/or automated management (of its subparts). For instance, in order to allow certain rooms in the house (e.g., the living rooms) to be heated and others (e.g., the garage) not for a certain period of time, an operating panel may be provided for every radiator turning it on and off or even measuring the current temperature and matching it with a predefined temperature goal. In more advanced settings, a central management unit at the level of the house could be provided in which a goal temperature for multiple zones could be specified. Based on this information, heat can be released by those radiators standing in zones in which the temperature is lower than specified.

VI. AIR CONDITIONING PATTERNS

In this section, we consider the air conditioning utility within houses as a cross-cutting concern. Whereas heating as discussed in Section V aims to increase the room temperature within houses in case the temperature is lower than desired, air conditionning aims to decrease the room temperature in case the temperature is higher than desired. We consider the integration architectures for air conditioning as proposed in Section II at the modular granularity level of a house, room and brick. Afterwards, we consider some advanced issues and reflections.

A. House level

In case houses are equipped with an air conditioning system, some houses have a centralized, electricity driven, cool air producing unit. This cold air is then distributed along the different rooms in the house later on (cfr. infra). Considering the granularity level of a house, this therefore means that typically integration pattern 1 is opted for (and more specifically 1B, as most households use a standardized cool air generator for this purpose). We are not aware of any air conditioning generation/distribution at a higher granularity than a house, such as a city or community as was the case for electricity and heating, which would allow houses to tap cooled air from an external network. This would constitute a configuration 2A or 2B at the level of a house, and 1A or 1B at the city or community level. As we can imagine several very challenging issues of such configuration and given the fact that the market base for air conditioning is currently still rather limited, we leave this aggregation level out of scope. The current way of working clearly implies certain benefits such as independence from external cool air generation providers.

B. Room level

In contrast with the electricity and heating concern, not all rooms (or even the majority of them) within a house are always equipped with air conditioning if a house has provisionings in this regard (e.g., only the bedroom and living room). We mentioned above that some houses employ a central cooling system in which cooled air is produced at one centralized place in the house. This heat is then transported via tubes to the required rooms in which an air fan is present. Therefore, such situations correspond to configuration 2 at the level of the rooms. For the authors, not being experts in air conditioning as well as the other cross-cutting concerns, there is no full clarity regarding the fact whether this constitutes a 2A (custom built) or 2B configuration. However, this issue is not due to a shortcoming of our modularity or integration pattern reasoning, but solely due to our lack of expertise in the specific area of, in this case, air conditioning. It is obvious that this configuration allows an efficient generation of cool air but also clearly entails a dependency of all rooms on this central cooling system: in case it would fail or be replaced in such way that the old tube network no long suffices, all rooms would be heavily affected. Using a framework gateway, which decouples the pipe network from the cooling system, might prevent this and would even allow to switch between different sources of cool air production. This would correspond to integration architecture 2C. In many houses having air conditioning, no central cooling mechanism is present. Instead separate (mobile) air conditioning devices are put into each room to be cooled (with a hose to be connected to the outside environment to expel hot air). Therefore, this corresponds to integration architecture 1 (and more specifically 1B as it generally concerns highly standardized devices). As we know from our discussion above, this configuration implies the duplication of these air conditioning devices in each room for which cooling is preferred.

C. Brick level

Just as we discussed for the case of the electricity and heating cross-cutting concerns, we might envision the integration of the air conditioning cross-cutting concern at the level of an individual brick as a purely thought provoking possibility, as represented in Figure 1 [2]. In every such element, standardized transport pipes would be embedded for the transportation of cooled water or air, nicely fitting onto the pipes of every similar adjoining brick. This would provide a remarkable degree of scalability when compared to the traditional integration alternatives: as different rooms are built or expanded throughout time, additional bricks (with integrated pipes) could be used, enlarging the area that can be cooled. Clearly, just as it was the case for the device level for the electricity and heating concern, the brick level seems to represent the most fine-grained modularity level at which the heating cross-cutting concern can be meaningfully integrated.

D. Overview and advanced issues

Table III provides an overview of the granularity-integration pattern combinations for the air conditioning within houses. While at first sight, the air conditioning might seem completely analogous to the heating concern discussed before (i.e., cooling instead of heating), some important differences and nuances can be observed. First, airconditioning is not a mandatory or strictly necessary cross-cutting concern within houses. Indeed, many houses or buildings exist in which no airconditioning is present (which may in fact even represent the majority of the houses). Secondly, somewhat related or being a consequence of the previous point, is that the way how the air conditioning concern is integrated within the modular structure of houses is less mature when compared to heating. No concern provisioning is, to the best of our knowledge, present at the level of a city or community. And while the concern provisioning at the level of the house and room is standardized in case of configuration 1, this is not the case (or at least not completely clear) when configuration 2 is opted for. Therefore, we anticipate that these 2A configurations will or can tend towards a configuration 2B (and later on 2C) in the future, as the domain further gains maturity. Next to the exploration of possible air conditioning management at the level of cities and communities, these transitions might constitute interesting avenues for research. Also here, we might propose to consider the integration of the cross-cutting concern at an even more fine-grained level (i.e., a brick) in the future. Moreover, these findings correspond with our intuition that a concern with a somewhat lower adoption rate exhibits a somewhat lower degree of maturity.

TABLE III. OVERVIEW OF THE DIFFERENT GRANULARITY-INTEGRATION PATTERN COMBINATIONS REGARDING AIR CONDITIONING.

	1A	*1B*	*2A*	*2B*	*2C*
city/community	○				
house		●	○		
room		●	●		
brick				○	

●: currently employed, ○: to be explored

Further, it should be clear that also the air conditioning cross-cutting concern is highly related to the way how insulation is managed and that the same modular aggregation levels might be relevant: the house (e.g., an isolating roof), the room (e.g., a well-closing door or insulation being put behind a wall) and the brick (e.g., insulation incorporated in every individual brick).

VII. INTERNET ACCESS PATTERNS

In this section, we consider the need to provide Internet access within houses as a cross-cutting concern. We consider the integration architectures as proposed in Section II at the modular granularity level of a house, room and device. Afterwards, we consider some advanced issues and reflections.

A. House level

Within most cities and communities in developed countries, access to Internet access is considered as a crucial resource for all inhabitants. As it is typically required to distribute such

Internet access across all houses within such community, it can be considered as a genuine cross-cutting concern. The main connections for Internet, being considered as a network of networks, are formed by backbones constructed by government and Internet provider companies (the so-called Tier 1, Tier 2 and Tier 3 networks). When we discuss Internet access as a cross-cutting concern in this paper, we mean the way how an artifact connects to an internet connection provided by an Internet provider in its area.

In order to obtain such connection, most houses have an individual subscription to an Internet provider (e.g., through a connection achieved by fibre). This provider will make sure that the subscriber gets an IP address, can access the Internet by downloading and uploading information, etc. So while the Internet itself is clearly to be considered as an external framework, the access point is provided at the level of an individual house. Therefore, when studying the way how the connection to the Internet is made, this can be considered as the usage of integration pattern 1B (as typically, standardized routers —sometimes even provided by the Internet providers— will be used for this purpose). Such integration provides certain appealing characteristics. This configuration allows each household to make independent choices (e.g., to subscribe or not subscribe to an Internet connection) and flexibility in terms of the Internet provider of their own preference.

B. Room level

Within every house or building, most if not all rooms require Internet access these days in order to use TVs, radios, computers and other devices in a meaningful way. Therefore, it constitutes a cross-cutting concern at this level as well. In most contemporary designs of houses, rooms connect to the Internet connection as obtained at the level of the house (configuration 2), instead of subscribing and making a separate connection on their own. This can be due to the fact that separate Internet subscriptions are considered overkill for each room (given the large download and upload limits for each single subscription) as well as the fact that the internal network within the house (connecting the devices within one house) is typically distributed via the same medium and technology.

The distribution of the Internet connection to rooms can be done via different media. For instance, UTP cables having a RJ45 connector can be drawn within the walls or on the ground to which many digital devices can connect. Another option is to opt for the wireless distribution of Internet access via Wifi. While it could be that the router making the initial connection with the Internet provider (see Section VII-A) already provides a Wifi signal that can reach one or multiple rooms, Wifi repeaters (capturing and repeating the Wifi signal in order to extend the network) are generally required in (some) rooms. Alternatively, the network and Internet access can be distributed via so-called powerlines, in which the signals are distributed over the electricity network (see Section IV) and captured via plugs in the electricity sockets, which expose the signals via Wifi or a connection for UTP cables.

Typically, the above mentioned connection points for the provisioning of Wifi within the rooms of a house are standardized. In some cases, the repeaters or plugs might be specific for the Internet provider chosen. This means that, in case another Internet provider would be chosen later on, different repeaters or plugs might be required and configuration 2B is adopted. In some cases, such as with the use of UTP cables and RJ45 connectors, no Internet provider specificity is present within the access point at the level of the room and therefore configuration 2C is present: one could easily change the chosen Internet provider without an arising need to change the connectors.

C. Device level

While Internet access is distributed among the different households and their rooms, the Internet access should ultimately be disclosed to individual devices for which it is required in order to work properly and provide access to Internet services. The most straightforward solution would probably be to use the provisioned UTP or Wifi connection at the room level (see above) for connecting the devices. This would correspond to configuration 2. More specifically, as most devices use a highly standardized network card as a relay to the house level Internet connection, this generally corresponds to a 2C configuration as changing the Internet provider would not impact these connections. In some cases, one might argue that configuration 2B is still applicable as sometimes, a change in Internet provider might require the adaptation of certificates, username and/or password.

As another possibility, devices can perform their connection to an Internet provider themselves in a dedicated way. This means that they do not use the room or house level provided Internet access but instead will access the Internet via a separate subscription. One might think of smartphones having a mobile subscription with a data package and accessing the Internet via a 3G or 4G connection. Or of all kinds of other devices connecting to LoRa or Sigfox services in order to access the Internet. In the context of the ever increasing popularity of the IoT, it is interesting to see that our modularity and integration pattern reasoning as set out in Section III clearly indicates that such configuration is highly suitable for such purposes due to its associated independence and flexibility in terms of the choice of a provider. However, this implies that the configuration and connection capability to the mentioned IoT services should be duplicated in each of the devices. Recall that we also made a brief referral to the IoT context during the discussion of the same integration pattern of another cross-cutting concern as well (see Section IV-D).

D. Overview and advanced issues

Table IV provides an overview of the granularity-integration pattern combinations for the electricity provisioning of houses. We can observe that, at all modularity levels, a standardized integration pattern (i.e., 1B and 2B) is opted for, with in some cases even a 2C configuration (indicating the presence of a framework gateway). This tends to indicate a rather high maturity within the respective domain, which could be argued to be rather congruent with our experiences in everyday life: indeed, in most cases today it is rather easy to equip an increasing amount of devices in a household with Internet access. While the table does not explicitly indicate integration patterns to be explored and researched for this cross-cutting concern, the next section (see Section VIII) will suggest some general possibilities for exploration that are also applicable for this Internet access cross-cutting concern (especially in case one is opting for the distribution of Internet access by the use of UTP cables). Further, the table once again illustrates that, when aiming for maximum flexibility, the integration of concerns tends to be solved at more fine-grained levels (going downwards in Table IV) and in a more standardized externally enabled way (going to the right in Table IV) in the long run.

TABLE IV. OVERVIEW OF THE DIFFERENT GRANULARITY-INTEGRATION PATTERN COMBINATIONS REGARDING INTERNET ACCESS.

	1A	*1B*	*2A*	*2B*	*2C*
house		•			
room				•	•
device		•		•	•

•: currently employed, ◦: to be explored

VIII. REFLECTIONS

Sections IV till VII showed that the integration of cross-cutting concerns such as electricity, heating, air conditioning and Internet access can and have to be dealt with at several modular granularity levels and can be solved in multiple ways. During the drawing of a building plan, an experienced architect will take into account these cross-cutting concerns in advance: the wires for the electricity and water pipes for the water distribution will be provided, space for central heating boiler will be assured, and so on. And although some heuristics and best practices exist, this still means that the integration problem of these concerns has to be dealt with by every architect again, every time a house is constructed. As mentioned in Section II, NST was inspired by the need for adaptability and flexibility. In the context of a house, this would for instance correspond to the possibility of incorporating an additional room, or choosing another provider for a particular cross-cutting concern (e.g., switching from tapping electricity from the public distribution network to self-generated solar energy). However, it is generally known that the distribution of housing cross-cutting concerns —such as the ones we considered in this paper— may cause significant problems during such house extensions or adaptations. Many times, this leads to unforeseen ripple effects, including the drilling into walls and floors, and even tearing down (parts of) walls. As we explained in Section II, NST therefore proposes to use a set of predefined design patterns (called "elements") that already solve this integration problem for a particular functionality of a modular system and can then be used over and over again.

In the context of housing and their cross-cutting concerns, we would envision an elementary construction element as such fine-grained element [2] as is represented in Figure 1. We already suggested such a brick for heating and airconditioning, but it is clear that a construction element might provide the integration of more than one cross-cutting concern (e.g., water supply, electricity, physical support, wired Internet access provisioning, etc.). Different types of such building blocks might exist, such as for inner or outer walls, for floors and ceilings, with and without certain utilities, etc. The adaptation problems and their associated ripple-effects would be less frequent by the use of such building blocks as it is often the set of cross-cutting concerns that causes these invasive drilling and tearing down activities and these would then already be integrated in the most elementary building block of a house. As they are used, the construction elements would provide the cross-cutting concerns and integrate fluently with the other previously installed building blocks. Moreover, an architect designing a new house would have to spend less effort into the integration issues regarding the cross-cutting concerns as the elements already deal with it. As we are no domain experts, we are not in a position to elaborate in detail how these building blocks should actually look like in practice. However, we do think that it would be worthwhile for such building blocks to be subject to intensive research and development, which might for instance result in connections and isolations of fluid conduits and electrical conductors that are superior with respect to handcrafted plumbing. As these building blocks would be rather general and used over and over again, the resources invested would have a significant pay off due to the high-quality re-used solution.

So while in most cases, architects take the house as the main level of modular granularity, it is interesting to see that some initiatives have been initiated to adopt the individual rooms of a house as a modular unit. It even seems that some kind of elements have been proposed in this context, such as in the Hivehaus "modular living space" initiative [9]. Here, houses are assembled as aggregations of prefabricated (e.g., hexagonal) modular parts, wherein the distribution of auxiliary facilities has been integrated upfront. Clearly, the design freedom concerning the house is then limited to an aggregation of these modular building blocks. This is due to the phenomenon we mentioned in Section II: the cross-cutting concerns should be integrated at the most fine-grained modular level as possible, as this determines the flexibility of the resulting artifacts. It is for this reason that we encourage the exploration of a construction element, integrating several cross-cutting concerns as discussed above.

Finally, we wish to remark that very similar conclusions or analyses can be made for other utility concerns within houses such as water distribution or media (audio, video) as well. We anticipate that the bottom line of such analysis will be highly similar: first, the distribution of the cross-cutting concern should be considered at different modular aggregation levels. At each level, centralized (integration pattern 1) or non-centralized (integration pattern 2) integration patterns can be chosen, each in a non-standarized (A) or standardized (B) way. Whereas the decentralized version offers benefits in terms of freedom of choice, the centralized alternative might typically generate other benefits such as economies of scale. A centralized version then has to deal with the fact that all modules plugging in are dependent on the framework unless a gateway module assuring version transparency (2C) is used.

IX. CONCLUSIONS

This paper presented an overview of the different possible integration patterns (with their associated benefits and drawbacks) for the heat, electricity, air conditioning and Internet access distribution utilities in a housing context, which we consider as cross-cutting concerns within a modularity perspective. It is important to stress that none of the authors claim to be experts in any of the specific cross-cutting concerns discussed (e.g., electricity, heating, etc.). Instead, the analysis was based on general knowledge within this domain. Also, with regard to general modularity reasoning, no significant new principles or knowledge was presented. Our actual contributions are situated elsewhere and are twofold. First, our goal was to show that the cross-cutting integration patterns for modular structures as proposed in [2] (and illustrated within the domain of software systems) are, at first sight, indeed relevant and applicable in a domain outside software as well. Given our non-expert status in the housing industry, we encourage actual domain experts to scrutinize and validate or refine our initial analyses. Second, we proposed and illustrated an approach to analyze and report on the different modular integration patterns for cross-cutting concerns within a domain. That is, is seems valuable to start with describing certain specificities and challenges in the domain at hand. Next, the different (hierarchical) granularity levels in the domain as well as the relevant cross-cutting concerns could be listed. For each cross-cutting concern, all possible combinations of granularity levels and cross-cutting concern integration patterns can be considered and analyzed in terms of their respective benefits and drawbacks. Some of these configurations might already exist, others might prove to be interesting avenues for future developments and still others might be purely theoretical considerations. We find it encouraging that we recently succeeded in applying the same thought experiment (i.e., applying modularity reasoning in terms of the possible integration architectures for cross-cutting concerns) within another domain (being artifacts and concepts related to logistics) [12]. Therefore, we hope that this paper might incite researchers and experts within other domains (e.g., all kinds of manufacturing and product designs) to perform similar analyses within their respective areas of expertise.

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