Business model analysis of Geo-TABS buildings with predictive control systems

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Abstract. This paper investigates the conceptual framework and impacts of business models in model predictive control (MPC)-based geothermal *Thermally Active Building System* (Geo-TABS). The analysis is done by compiling technical, political, economic, social and environmental analytical frameworks of MPC Geo-TABS. The elements of the business model Canvas are identified and analyzed in this application. Theoretical bases of business model generation are verified by substantiating arguments and potential profit analysis for stakeholders via four demonstration buildings. The focused building types/cases involve office building, schools, elder-care houses and multi-family house. Methods to verify the proposed value propositions in the business model are given special interests. The results show that correctly sizing and combining the four major components: MPC, geothermal, TABS and suitable building types, are the core in both technical and business development perspectives. Complete design guidelines are crucial for promoting MPC Geo-TABS business in its service chains. Transforming the conventional economy-oriented business development method to holistic sustainability-oriented profit matrix can further strength the value propositions of MPC Geo-TABS. The findings aim at supporting decision-makers and further improving engineering guidelines in implementing MPC based Geo-TABS in a larger scale in Europe.

Keywords: Business Model, Geo-TABS, MPC, Sustainability, EU Buildings

1 Introduction

1.1 The concept of Geo-TABS

Building sector is one of the largest energy users, which accounts for approximately 32 % of global energy usage (1). In European Union (EU), energy usage in buildings has increased from 400 Mtoe to 450 Mtoe in the past 20 years, and this increase is bound to continue if adequate energy saving measures are not carried out (2). Development and promotion of new methodologies and technologies to contribute to the future regulations and technical solutions have been addressed by both the loaded EU and International Energy Agency directives (3). The involved policies require member states to implement energy-efficient measures in both existing and new buildings, aiming to accelerate the transformation of EU buildings towards Net-Zero energy/emission buildings. Additionally, energy performance/sustainability certificates are to be included in all advertisements for the sale or rental of buildings (4).

In order to meet these EU energy and climate landscapes, Thermal Active Building System (TABS) has emerged as an innovative solution to improve building energy performance and indoor climate. TABS combining cooling and heating system in the structural concrete slabs/walls of a multi-storey building, which is able to operate hydraulic temperature close to ambient temperature, such as 22-28 ℃ for heating and 16-20 ℃ for cooling (5). TABS are primarily for sensible cooling and secondarily for base heating. The whole system works with radiant heating and cooling, which is not any air-conditioning or radiators, and does not commonly substitute any ventilation system. Furthermore, TABS stores heat via building structures themselves and can commonly provide upgraded global thermal comfort than conventional convective heating/cooling methods (5). Due to the reduced draught, noise levels and improved mean radiant temperature through less fluctuated surface temperature, local thermal comfort is commonly high in TABS buildings (6). All the above advantages have promoted TABS as a competitive heating/cooling emission system in the current EU building markets.

From a sustainability perspective, TABS-served low-temperature heating (LTH) and high-temperature cooling (HTC) provide wide opportunities for the integrations and applications of renewable energy, such as geothermal energy or ground-source heat pumps (hereafter refer as Geo-TABS), in which the coefficient of performance (COP) can be largely improved. This further reduces the operational costs for heating and cooling. However, due to the nature of large thermal mass in TABS buildings, this system responses very slow comparing to conventional convective heating/cooling system, such as radiators and air conditioning. This leads to a high requirement to the operating conditions and controlling of geothermal systems in certain conditions: such as peak loads during heating/cooling seasons. As introduced above, Geo-TABS buildings need more advanced self-tuning control strategies in order to fully utilize the potentials. Hence, further improve the responding time and energy performance of such system comes into question. In recent years, a model predictive control (MPC)-based Geo-TABS system has been technically developed and implemented in several European buildings (7) (8) (9). However, most of the implementation and analysis of existing MPC Geo-TABS practice were carried out on a case-to-case base (10) (11). The business guidelines are highly case-driven and lacking of systematic indications. How to characterize the value proposition (VP) of combining MPC with Geo-Tabs, and how to qualitatively evaluate such system in a large scale are still not sufficiently reported. From corporate level, developing a high-level business model that can lead to approaches and conceptual frameworks for engineers, managers and stakeholders to further explore the market values of such systems are not attained. More importantly, few studies have explored the usage of business model in promoting MPC Geo-TABS, and examining barriers to evaluate such system in market, social, regulatory and financial aspects in a systematic approach. A clear business model and analysis scheme for the future supply, design, commissioning, operating and maintenance (O&M), and monitoring are in need.

1.2 Objective

The objectives of this paper can be listed us:

- The system scheme of MPC Geo-TABS components and working principles for the selected building types
- The proposal of business model for MPC Geo-TABS building and potential evaluation methods

2 Applications of MPC: state of the art and system frameworks

2.1 The principle of using MPC in Geo-TABS

As introduced in Section 1.1, TABS works with hydraulic temperature that is close to the ambient. For heating seasons, the $\theta_{supply}/\theta_{return}$ are 28 ℃/26℃, given the room temperature of 20℃. The maximum heating capacity of standard TABS are $25W/m^2$. High performance TABS (embedded pipes close to concrete surface) can provide maximum heating capacity around 40-50 W/m^2 (5). For cooling seasons, the $\theta_{supply}/\theta_{return}$ are 16 ℃/19℃, given the room temperature of 26℃. The maximum cooling capacity of standard TABS is $40W/m^2$. High performance TABS can provide maximum cooling capacity around 60-80W/m^2(5). Based on the local climate and heating/cooling loads, the low-temperature heating (LTH) and high-temperature cooling (HTC) working principle of TABS provides broad opportunities to improve the COP of GSHP, which further saves electricity (El) usage of compressors. Fig.1 shows the system scheme of Geo-TABS components and working principles. It can be seen that TABS works with a “zone-to-zone” basis and these “zones” are defined in the early building design stage. When TABS is connected with geothermal, modern GSHP commonly is able to work with diverse working modes based on the sizing and energy demand of TABS “zone”(12). These modes can be listed as:

- Base heating control mode: Geo-TABS provides base heating during non-peak load time in heating seasons
- Dual mode: when heating and cooling loads are existing year-round, such as for office buildings in some selected climates

- Active cooling control mode: Geo-TABS provide cooling during cooling seasons
- Passive cooling control mode: At sufficient temperature level of the ground, GSHP operates in free cooling mode which only circulation pumps are involved

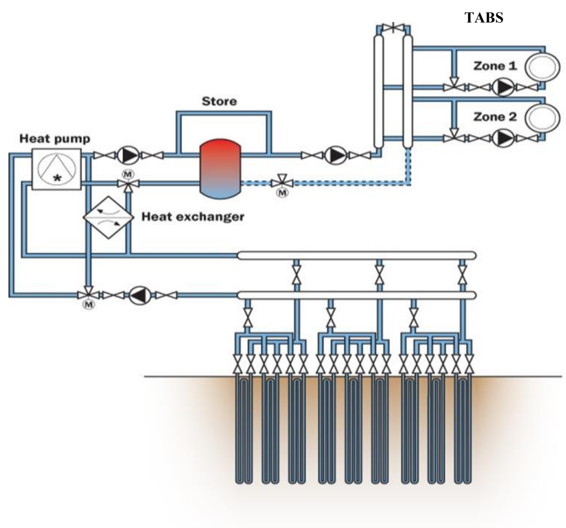

Fig. 1. A system scheme of Geo-TABS components and working principles (5)

Additionally, the controlling strategy may differ in Geo-TABS based on how advanced control system the building needs. For example, three conventional controlling strategies are used jointly with the above working modes (13):

- 24 hours operation: this controlling strategy allows pumps to work through continuous operation in 24 hours with a constant θ_{supply}. This strategy largely depends on the behaviors of TABS by its self-regulating effect; it is not demand-optimized and leads to continuous El usage for compressors.
- Day-night operation: this strategy loads the building thermal mass during the night and let the heat be delivered to the room during the day. It highly depends on the storage capacity of the mass, and GSHP works according to the simple principle of "On/Off", which is only suitable for buildings with well-scheduled occupancies and high thermal mass, such as concrete core-activated offices.
- Cyclic operation: this strategy allows TABS to be operated in selected time intervals, which is also considered as "pulse width modulation" (13). The core of this strategy lies in learning the ambient temperature compensated θ_{supply} with pulse width modulation (via constructing heating/cooling curve with respect to θ_{set}).

As introduced above, MPC was introduced as an innovative application in order to solve the dynamics of building energy demand instead of constructing simple heating/cooling curve by long learning process, as the conventional controls. MPC selects and identifies the building energy demand model, and further optimize the working strategy of Geo-TABS well ahead of time, in order to achieve the targets of: controlling GSHP to supply correct mass flow with sufficient θ_{supply}, under approximate working modes of heat pump groups. The predictions allows the optimization to select the best control parameters that can minimize the energy usage, while at the same time without compensating thermal comfort (or other objective functions). The general MPC optimization principle can be outlined as (14) :

$$Minimize_{u_t,\dots,u_{t+T-1}} \sum_{k=t}^{N-1} f(x_k, u_k) \quad (1)$$

Subject to: $$x_{k+1} = g(x_k, u_k, d_k), \text{ where } k = t, \dots, t+T-1 \quad (2)$$

$$x_k \in X_k, u_k \in U_k, \quad (3)$$

In which the predicted results (at time t) are generated from the prediction model Eq.(2). The predicted input parameters and conditions are constrained to the settings of Eq.(3). The initial condition of $x_{t=0}$, optimizer Eq.(1), generate the results $u'_0, \dots, u'_{N-1}$ by control data inputs. And these results are optimal with respect to Eq.(1). In this way, a particular choice x_k and u_k is assigned by the function$f(x_k, u_k)$. However, this standard MPC concept may not be applicable in all cases of Geo-TABS in reality. The reason is that disturbances $d_k$exists. d_k can be subject to outdoor temperature, building types, internal heat gains (from both solar and occupants), as well as building usage schedules, etc (14). And some parameters of these d_k can be random, such as outdoor temperatures. Therefore, a good understanding of how MPC should be coupled with Geo-TABS, more importantly, what HVAC components are available and linked in the selected archetypes are important. Existing studies have reported that building control system should be developed in the pipeline of early-stage building design. A good understanding of the implemented building types provides flexibility and low-risk experimentation [9]. A high-level system framework can further assist the development of deterministic formulations of d_k, by either bounded constraint (robust MPC), or probabilistic model (stochastic MPC).

2.2 High-level framework of applying MPC Geo-TABS in the building types

Based on the MPC concept introduced in Section 2.1, it is believed that MPC is mostly suitable as a top-level controller to optimize set-points of lower level controllers (11). Therefore, a high level framework of applying MPC Geo-TABS in four selected building types are developed, shown in Fig. 2. The included building types cover office, school, care house and residential buildings (multi-family). Different modules provide information and interactions of HVAC components. The framework classifies two types of flows in all Geo-TABS systems: energy flow (black solid line), and communication flow (black dashed line). Constrain settings in Eq. (3) and d_k are generated by back arrows to MPC. Prediction signals based on prediction model Eq. (2) are generated from MPC along the out-going arrows to different modules in Geo-TABS. A benchmark system is further developed in order to verify and compare the advantages of combining MPC with Geo-TABS, based on the selected building types and current HVAC system in EU building market (15), shown in Table 1.

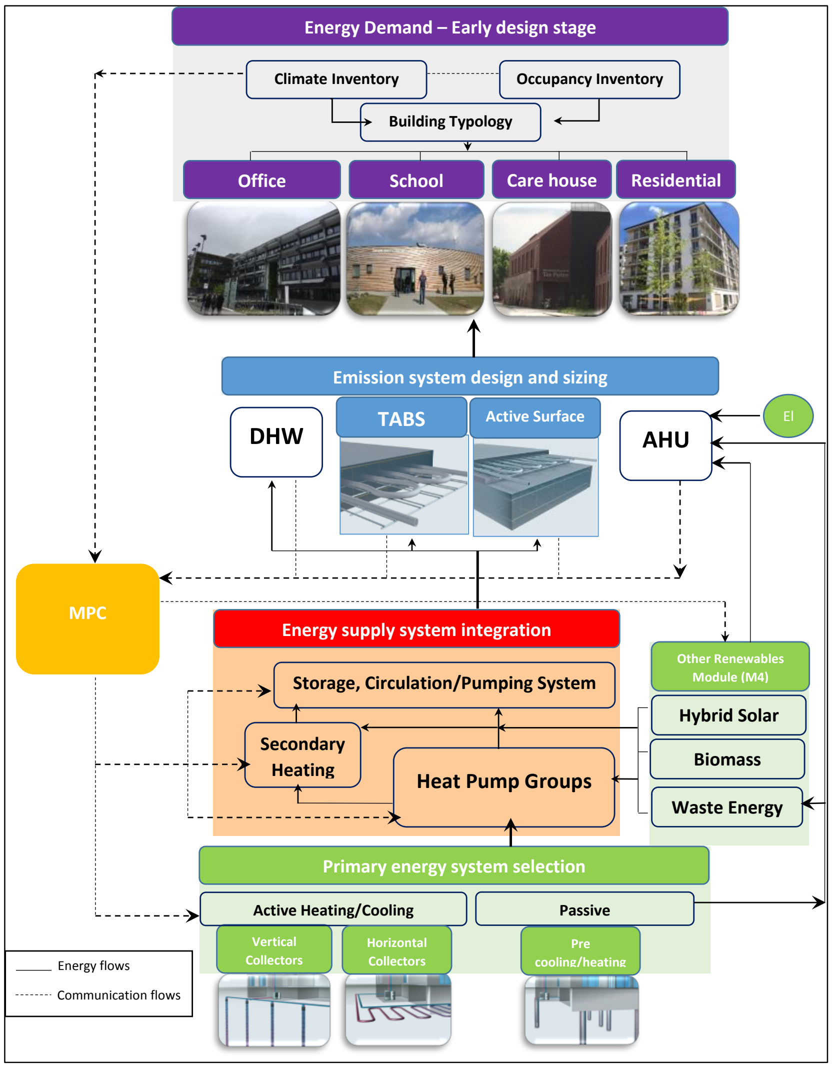

Fig. 2. A system scheme of MPC Geo-TABS components and working principles

Table 1. The benchmark systems for MPC Geo-TABS.

Building Types	Benchmark	MPC Geo-TABS
Office buildings	District heating/cooling +	GSHP + TABS heating/cooling +

	boilers +Fan coil units/Chilled beams + Mechanical ventilation with heat recovery + Conventional feedback control	Passive cooling + Boiler as secondary energy for DHW + Mechanical ventilation only for required indoor air quality + other renewable alternatives + MPC
Residential buildings	District heating/boilers + radiators + Mechanical ventilation with heat recovery + Conventional feedback control	GSHP + Thermal active surface (floor) heating + Exhaust ventilation with heat recovery + other renewable alternative + MPC
Care house	District heating/boilers + radiators + Fan coil units + Mechanical ventilation with heat recovery + Conventional feedback control	GSHP + TABS for heating/cooling + Secondary system + other renewable alternatives + Mechanical ventilation with heat recovery + MPC
School	District heating/cooling + Radiators + Fan coil units + Mechanical ventilation with heat recovery + Conventional feedback control	GSHP + TABS for heating/cooling + Boiler for DHW + Mechanical ventilation only for required indoor air quality + MPC

3 Business model analysis on MPC Geo-TABS

The application of business model in MPC Geo-TABS are based on the theoretical bases of business model generation Canvas (16). In principle, business models are designed and executed in specific environments that adapted to this case can be depicted mainly on three aspects – market forces, industry forces and key trends. Utilizing a business model approach for the assessment from both source and end-use will ensure a more commercial driven analysis aimed at identifying a hygienic and sustainable water supply system. Information extracted from stakeholder insights analyses, understanding the "jobs they are doing" and the "pains" and "gains" they have, will form a good basis to derive relevant value propositions for realizing the concept. The structure of business model canvas is commonly composited by 9 key elements, centered by value proposition. The development of these 9 key elements are commonly conducted by brainstorms among the key players in the whole life of the project: such as consortium, stakeholders, developers, investors, customers and marketing agents as well as commissioning partners. Fig. 3 shows the business model for MPC Geo-TABS linking these 9 basic elements. These results are expected to provide an early-design stage indication that how MPC Geo-TABS should be promoted from a business perspective. The business model in Fig. 3 was developed based on the principle of sustainability on an interactive and iterative process around value propositions involving multiple cooperation partners.

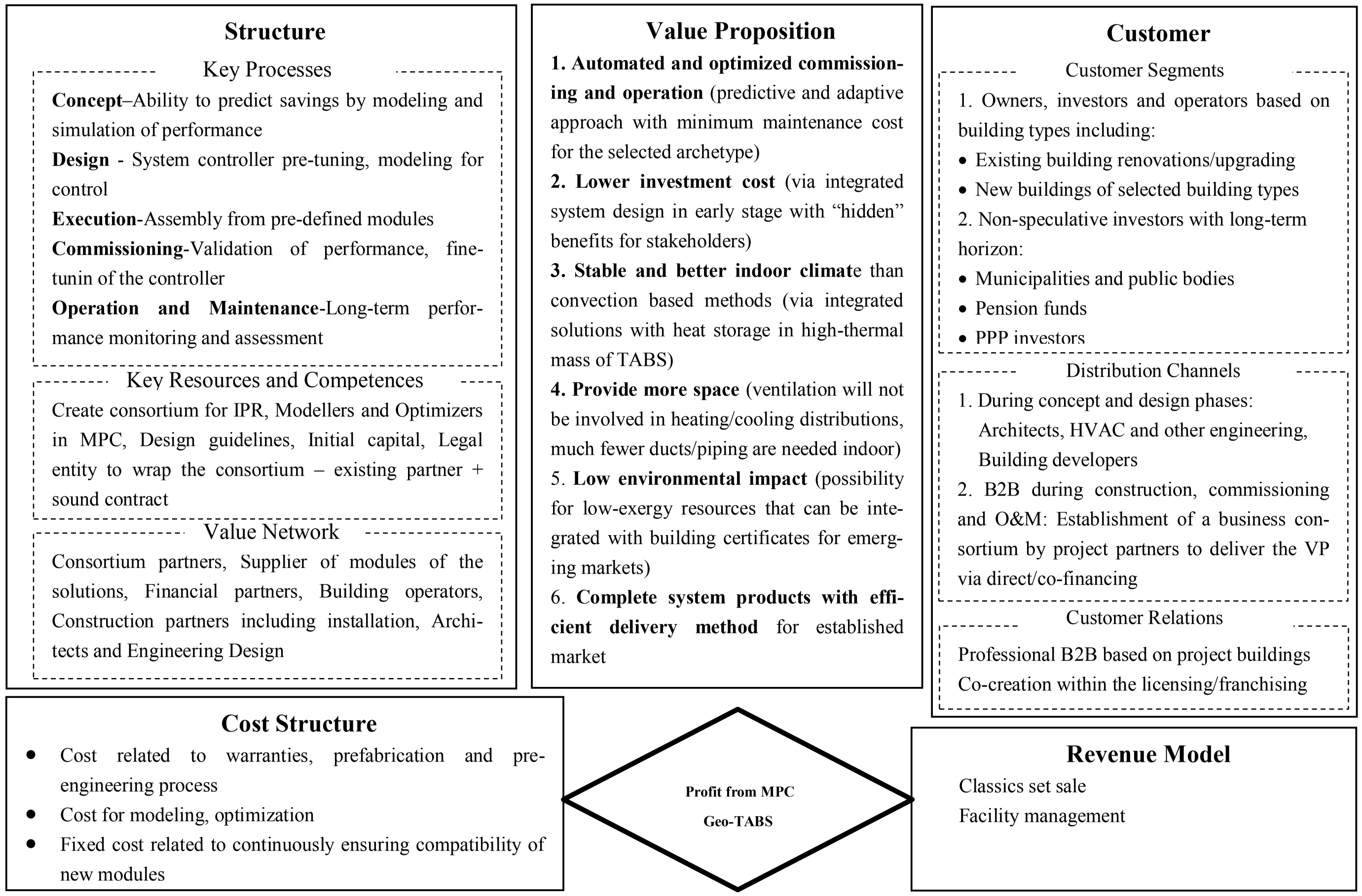

Fig. 3. Business model development for MPC Geo-TABS

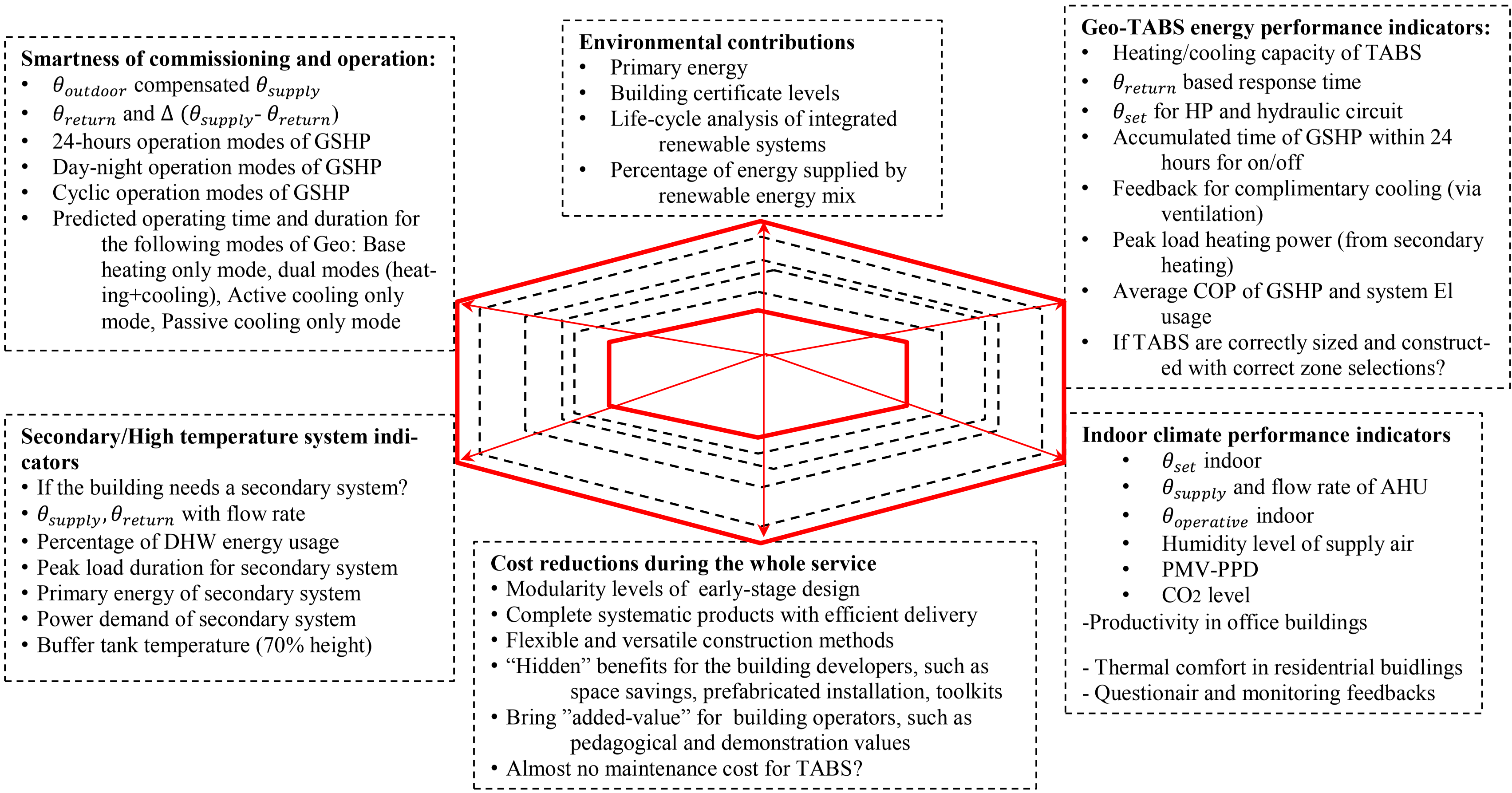

Fig. 4. Analysis and evaluation guidelines for the VP of MPC Geo-TABS based on indicator scoring scheme

Three key dimensions, namely, value proposition, distribution channel and cost structure, are believed to be key importance, with respect to building types, current Geo-TABS markets and technical innovations. The core of this business model is the proposed value proposition, presented in the center of Fig.3, which are formed by six key perspectives. Distribution channel of MPC Geo-TABS is addressed based on two market categories: established market and emerging market, via three representative building types: office building, residential building and public buildings. Three cost structure are addressed by formulating the major and unique costs of MPC Geo-TABS: by cost related to warranties, prefabrication and pre-engineering process, fixed cost related to continuously ensuring compatibility of new modules. Based on this business model, a detailed analysis focusing on how to verify the proposed value proposition is further presented, as shown in Fig. 4. The results of Fig. 4 is expected to construct a set of quantitative criterion system that are measureable for stakeholders to further validate the business model, and explore the limitations of current business model for MPC Geo-TABS in the market. This criterion system is structured based on the six key value proposition proposed in Fig.3, but further adapted to measurable parameters during the whole service life of MPC Geo-TABS. Each of the six criteria is constructed by a set of indicator/parameters, which can be quantified by modeling, on-site output measurements, monitoring, questionnaires and control system metering.

The indicator sets and evaluating guideline, shown in each criterion in Fig.4, is expected to be then constructed by a holistic rating scheme (shown as different layers in the center of Fig.4). The out-layer of the circle represents the highest "score" of the correspondent criteria index, which is weighted by the "sub-scores" of each quantitative indicator. In this way, the stakeholder networks are taken into account as a whole, whereas value propositions that occurred during the whole MPC Geo-TABS service life chain is verified and quantitatively evaluated to the entire range of stakeholders, occupants, building owners/developers, engineers and architects, beyond just customers and shareholders. Given the fact that TABS itself is already economically competitive, the sustainability criterion involved in MPC Geo-TABS is more detailed classified in Fig.4. This approach is expected to drive the transformation of common business model to "sustainability – oriented" business model for future implementing MPC Geo-TABS projects in EU building types. How to supply and verify the studied value proposition for identifying customer segments of MPC Geo-TABS will be further studied in details during the whole process of the project disseminations.

4 Conclusion

It is concluded that business development of MPC Geo-TABS should be done by conducting a continuous dialogue with the main stakeholders of the building, via, e.g. validating anticipated performance, monitoring feedback, interview, occupant questionnaires and public network constructions. A systematic approach to visualize and score the gained experiences/knowledge should be further quantified and identified as references based on the local climate and social values. To have a successful business model for MPC Geo-TABS, correctly sizing and combining the four major components: MPC, geothermal, TABS and suitable building types, are the cores. Complete design guidelines are crucial for supplying MPC Geo-TABS business in its early design stage. Transforming the business development method to sustainability-oriented profit matrix can further identifying the customer segments and verify the value propositions of MPC Geo-TABS for the future large-scale implementation in EU building market.

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Nomenclatures	
AHU	Air-handing units
B2B	Business to business
COP	Coefficient of performance
DHW	Domestic hot water
Geo	Geothermal, including both active and passive ground-source systems
GSHP	Ground-source heat pumps
HVAC	Heating, ventilation and air conditioning
LT/MT/HT	Low temperature/Medium temperature/High temperature
IPR	Intellectual property rights
MPC	Model predictive control
PMV-PPD	Percentage of mean vote based predicted percentage dissatisfied
TABS	Thermal active building systems
VP	Value proposition
θ	Temperature, ℃

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