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The EFQM method to compare battery performance

Christophe Savard*, Chief Engineer, Teacher, Electrical Engineering, French Territorial Public Service, Reliability and Operating Safety, University of Lyon 1, 69100 Villeurbanne, France

Ali Sari, Full Professor, Electrical Engineering, University of Lyon, University Claude Bernard Lyon 1, F-69622 Villeurbanne, France

Pascal Venet, Full Professor, Electrical Engineering, University of Lyon, University Claude Bernard Lyon 1, F-69622 Villeurbanne, France

Anni Nikulina, Associate Professor, Economics Sciences, Department of Management, Saint Petersburg Mining University, 199106 Saint-Petersburg, Russia

Jerome Dupuis, Lecturer, Master Territorial Manager, Management Sciences, IAE Lille, University of Lille, 59 000 Lille, France

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Abstract

This paper links the scientific fields of electrical energy storage with that of managerial performance. It first presents the evaluation method of the efficient framework for quality management (EFQM) model, based on the criteria set interested in which way the management of an organisation acts on the results. An example fulfilling the requirements for an EFQM assessment is also summarised: the search for a high-performance battery internal architecture in order to improve its lifespan. To date, several different architectures, combined with a specific management algorithm, allow to similarly extending the battery lifespan. The method presented here helps to identify which architecture has the best management performance. In addition, it identifies its strengths and main defect.

Keywords: Battery, battery architecture, EFQM, performance, quality management.

* ADDRESS FOR CORRESPONDENCE: **Christophe Savard***, Chief Engineer, Teacher, Electrical Engineering, French Territorial Public Service, Reliability and Operating Safety, University of Lyon 1, 69100 Villeurbanne, France

E-mail address: cjs@mainate.com / Tel.: +353 (0)61 202700

1. Context

There are a number of methods to evaluate an organisation management performance (Sedliacikova, Mala & Satanove, 2018). These methods are intended to measure the effectiveness of human organisations. They are based on the performance search. Performance is often considered as the convolution of fundamental concepts, such as:

– the production by the organisation of a result greater than the sum of its members production;
– the production of value for the end customer;
– the maintaining sustainable optimal results;
– the respect for the sustainable development principles for the organisation and society;
– the best use of internal creativity and innovation and
– the management in a flexible manner, while charting the course, always seeking to improve external and internal performance.

If this last point can just consist in defining the methods to reduce the risks (considered as everything that can be contrary to the objective achievement), as for example by Rosu, Rohan and Juganaru (2017), to measure the managerial performance, it is essential to use an evaluation process such as the efficient framework for quality management (EFQM) Model, developed by The European Foundation for Quality Management. This framework allows, based on predefined indicators, to evaluate the effects of quality management mode on the organisation's performance. In the quality management field, there are different standards, mentioned particular in Akterian (2014). Among these standards, the ISO 9000 defines a continual improvement of the quality management system and the interactions between the different actors. The EFQM method is the multi-criteria. It can be applied to spheres other than pure management, such as, for example, in hotel industry (Liu and Ko, 2018).

Above all, an organisation is a complex system, implementing processes and using means to achieve the results. It, thus, appears possible to use the EFQM framework to measure the performance of a physical system acting on resources to optimise a result. One of the EFQM method strengths comes from that it finely evaluates the communication chains implemented. Thus, any physical system comprising a consequence part of information transfer seems adapted to be evaluated by a suitable EFQM framework because it is a powerful tool for decision support.

On the other hand, some physical problems come up against the question of relevant criteria for discriminating different solutions with similar results. The problem often arises of determining in the most complete way possible which is the most efficient among possible solutions. For example, for quality management in the battery manufacture, Schnell and Reinhart (2016) propose to split production into several stages. At each of them, quality criteria are evaluated. This quality assessment would improve battery manufacturing processes regardless of their technology. In methodological terms, the method must be adapted so that the criteria fit in with other spheres than pure management.

As a first step, the EFQM analysis grid is detailed in part 2 by recalling which are the nine criteria that compose it. Then, the sub-criteria and their quantification are presented as defined to evaluate the organisation managerial performance in part 3. In Chapter 4, the sub-criteria are suitable for the physical system analysis: the battery internal architecture. Before concluding on the relevance of deploying this method for technical solution assessment, a comparative analysis on three architectures is discussed in part 5.

2. The EFQM analysis grid

Ezzabadi, Saryazdi and Mostafaeipour (2015) affirms that EFQM is the most appropriate and best suited tool to evaluate organisations and leads in the path of organisational excellence. The method is often used in self-assessment of criteria grouped in a performance reading grid. Self-assessment is a good way to manage the organisation quality because it provides strong incentives for improving performance and adopting the methodology. It can serve as a motivational tool. However, the method has certain limitations. For Daniel and Naderpour (2018), the deployed assess nature is empirical. In addition, the assessor knowledge and skills level on the system to be evaluated may be suspected to be qualitative and subjective. The method also discretises the values of sub-criteria without differentiating whether these sub-criteria evolve linearly or not. To deal with uncertainty and inaccuracy, it is proposed to use fuzzy logic. The principle is similar to assigning for a variable a degree of membership to a predefined set. Thus, some researchers (Ezzabadi et al., 2015; Rohan & Rosu, 2017) propose methods to introduce fuzzy logic in the sub-criteria assessment, and thus reduce the subjectivity part in the result measurement.

This self-assessment is based on an exhaustive, systematic and regularly analysis performed on performance criteria. The EFQM model is based on three levels segregation: areas, criteria and sub-criteria, also called indicators. The analysis grid, shown in Figure 1, is structured in nine criteria that cover the main aspects of any organisational analysis. It comprises two areas: an area of factors affecting the managerial performance (enablers), including leadership, human resources, deployed strategies, physical and relational means as well as the processes implemented and an area of factors focusing on results: the operational result but also those obtained sustainably from employees, users and society in general. Following the self-assessment, the organisation has a snapshot of its managerial performance. It can then improve it and aims for the excellence achievement. The key to success of a successful management is to act on each lever, corresponding to an enabler area criterion, so as to progress towards performance.

In the enablers' area, criterion 1 focuses on leadership. Traditionally, the leadership has two pillars: trust and caring. Trust does not mean falling into laxity without setting an outline to the delegation. Caring means tolerating differences and using the staff wisely. The leader must define common values, codes of conduct and resolve conflicts. The leader develops the organisation vision by developing organisational values and systems for continuous success, all and facilitating the mission accomplishment. It is through his actions and behaviour, including ensuring internal stability during periods of change, that he affirms values and motivates staff with the right way. With a successful conception of the management system, the leader can focus on his core tasks, such as seizing opportunities, identifying risks and driving the trajectory leading to the desired result (Rohan & Rosu, 2017).

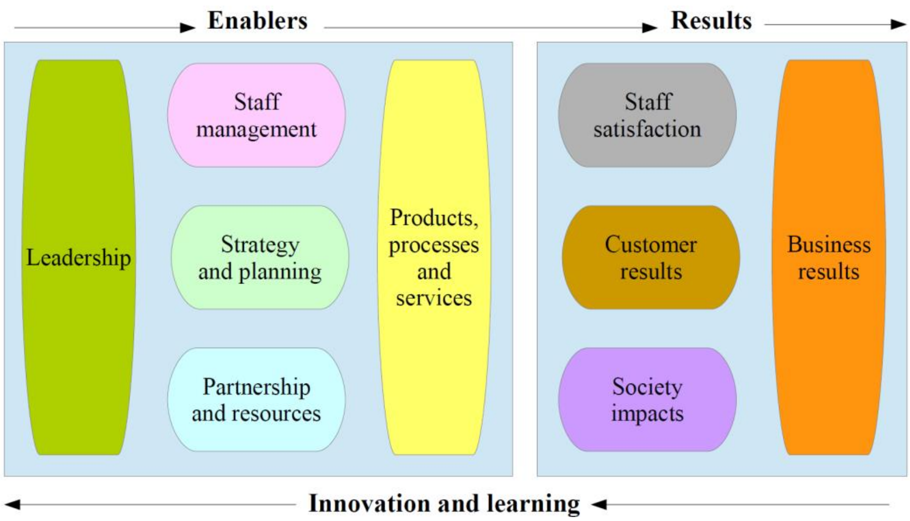

Figure 1. Measurement of excellence using the nine criteria of the EFQM model analysis grid

Criterion 2 assesses the organisation's strategy. This involves means (criteria 3–5). It implements all policies, plans and processes to achieve the set objectives. The strategy implementation is based on the planning of actions and changes.

Criterion 3 (staff) identifies whether the staff skills, knowledge and abilities are used by involving them in the organisation functioning and in the perspective of their own development. This also requires resources and their evolution planning. High-performance management values staff and creates a culture that supports personal and organisational goal achievement. Successful organisations promote the values of fairness and impartiality as well as the staff commitment.

Criterion 4 seeks to determine how and why both external partnerships and suppliers and internal resources are managed. This makes it possible to check whether they are used for the benefit of the defined strategies and policies.

Criterion 5 focuses on whether processes are planned, managed and continually improved. Processes include all the internal means other than raw material resources and human resources.

The organisation normally seeks to develop added value for customers and other stakeholders. The results area criteria assess this. Criterion 6 assesses the skills development and adaptive capacity of staff to achieve the objectives. Criteria 6–8 measure how staff, customers and society perceive the organisation's performance. Criterion 9 verifies whether the economic results are in line with the organisation's key policies and strategies. Sometimes, performance is based on this criterion only. A simple analysis of the result achievement merely examines this criterion, often measuring only the effectiveness aspect, and sometimes the efficiency.

3. Performance indicators

At the self-assessment end, a global score measures the managerial performance. It results from the weighting of each criterion. This weighting must be established before defining the indicators and must reflect the importance of each criterion in terms of the organisation's overall mission. As a result, the weighting is different from one evaluation to another (Daniel & Naderpour, 2018; Ezzabadi et al., 2015; Rohan & Rosu, 2017). A sustainable development aspect is included in the questions to evaluate the indicators. The EFQM purpose assessment is to improve methods, approaches and behaviours. To do this, it is necessary to act on the levers corresponding to the worst performing criteria of the five enablers in order to improve the worst results.

Each criterion consists of several indicators. It is evaluated by the total or partial reachment of a performance level, often metered on a discrete scale ranging from 'performance indicator achieved' to 'non-existent' through several intermediate levels, corresponding to a score from 1 to 0.

For the enablers criteria, the thresholds are as follows:

- no approach (score of 0);
- defined approach (score of 0.25);
- defined approach and implementation (score of 0.5);
- defined, implemented and measured approach (score of 0.75);
- defined, implemented, measured and self-improved approach (score of 1).
- For the result criteria, the thresholds are as follows:
- no result (score of 0);
- relevant indicators exist (score of 0.25);
- relevant and segmented indicators exist (score of 0.5);
- relevant and segmented indicators exist and meet defined objectives (score of 0.75);
- relevant and segmented indicators exist and meet defined objectives with a sustainable achievement of the result (score of 1).

For an organisation, the indicators commonly used reflecting the nine criteria are given in Table 1. The indicators for an organisation are the same for the result criteria (criteria 6–8), apart from the business result criterion (criterion 9).

Thus, structured EFQM method define the overall performance of an organisation (overall score), the impact on each stakeholder (result criteria), the possible improvement levers (enablers criteria) and the organisation weaknesses (indicators with the lowest notes).

Table 1. EFQM indicator list for each criterion

Criterion/ indicator	Description
1	Leadership
1a	The leader develops the mission, vision, values and ethical model of the organisation. He is exemplary and serves as a model.
1b	The leader defines, supervises, evaluates and leads the management system improvement and the organisation performance.
1c	The leader is personally involved with all stakeholders, including external partners.
1d	The leader reinforces a culture of excellence among the organisation employees.
1e	The leader ensures that the organisation effectively manages change and is flexible and adaptable.
2	Strategy and planning
2a	The strategy is based on an understanding of the stakeholders and the external environment needs and expectations.
2b	The strategy is based on understanding the organisation’s performance and internal capabilities.
2c	The strategy and its policies are developed, regularly evaluated and updated.
2d	The strategy and the policies that decline it are communicated, respected and managed.
3	Internal human resources (staff)
3a	Human resources management plans and policies are established in accordance with the organisation’s strategy.
3b	The knowledge and abilities of employees are identified and developed.
3c	Employees are managed, involved and empowered.
3d	Communication between all the different levels of the organisation is fluid and encouraged.
3e	Employees are rewarded and recognised. They receive a lot of attention from the organisation.
4	Partnerships and resources
4a	Partners and suppliers are managed with a view to sustainable profitable exchanges.
4b	Finance is managed in secure and cost-effective sustainability way.
4c	Buildings, equipment, materials and natural resources are managed responsibly.
4d	Technology is managed and developed in support of the strategy.
4e	Information and knowledge management is structured to enable effective decision-making and build the organisation capacity.
5	Process, products and services
5a	Processes are designed and managed to maximise the value of each stakeholder.
5b	Products and services are developed to create optimal value for customers.
5c	Products and services are promoted and marketed effectively.
5d	Products and services are produced, delivered and tracked with traceability.
5e	Customer relationships are managed and enhanced.
6, 7 and 8	6—Staff satisfaction; 7—Customer results and 8—Society impacts
6a, 7a and 8a	The organisation receives from 6—its clients; 7—its agents and 8—society; direct feedback on its performance through interviews, reviews, press articles, praise and

	complaints.
6b, 7b and 8b	The organisation has internal indicators to evaluate the effectiveness of its performance towards 6—its customers; 7—its agents and 8—society.
9	Business results
9a	The organisation has defined indicators to determine its strategy implementation success (measure of its efficiency).
9b	The organisation has defined indicators to determine the strategy implementation effectiveness.

4. Application Example

EFQM can be used to solve an optimality problem and contribute to the choice between different technical solutions that manage physical resources. Consider as an example the internal architecture of Li-ion batteries. A battery includes a large number of elementary cells (Kim & Shin, 2012), which can provide an electric current, when they are request to discharge. A cell is characterised by its open-circuit voltage and its nominal capacity, denoted Q_0, expressed in Ah (Yazami and Reynier, 2002). As a result, it is calibrated to provide a nominal current, noted I_{cell}, corresponding to the restore of all the electric charge contained in the cell in 1 hour. Thus, a cell with a capacity Q_0 = 20Ah can provide a current I_{cell} = 20A for 1 hour. To be able to store more electrical energy, the cells are associated in parallel. To be able to provide a greater voltage, they are associated in series. To identify the amount of electric charge that a cell contains at a time *t*, a state-of-charge (SoC) is defined as the ratio between the charge contained at time *t*, denoted $Q(t)$ and the capacity Q_0. In addition, a cell ages over time and its use (Wu, Wu & Wang, 2015). It is possible to retain by analogy the notions of aging and arduousness to understand the aging over time (calendar aging) and the aging with use (cycling aging). In a battery, not all cells can have exactly the same technical characteristics (Wen, 2009). In addition, they do not have all the age in the same way (Mahalakshmi and Datchanamoorthy, 2015). These disparities lead, at a given moment, the cells do not have all the same capacity or the same SoC. These disparities lead to premature aging of some over-solicited cells (Li, Pelissier, Venet & Gyan, 2016; Riviere, Venet, Sari, Meniere & Bultel, 2015; Wei, Huang, Sun, Cheng & Yen, 2016).

To reduce its undesirable effects and prevent cells from operating in dangerous situations (typically high temperature, over-charging and deep discharge), a battery management system (BMS) is added into batteries. Different operating reliability strategies, such as balancing between cell SoCs (Lu, Han, Li, Hua & Ouyang, 2013; Redondo-Iglesias, Venet & Pelissier, 2016; Shili, Sari, Hijazi & Venet, 2017a), are deployed to optimise stored energy and improve battery lifespan. Often the number of cells is greater than it could be to just meet the specifications of the external user. The BMS can, thus, activate or not each cell. To meet the external load specifications, it must, however, activate enough cells. Two obvious solutions are retained to realise the physical architecture connecting the cells: series-parallel (SP) and parallel-series (PS) (Savard, Niel, Venet, Pietrac & Sari, 2017). An example of a battery comprising four strings of two cells connected in parallel is given in Figure 2. The complementary electric scheme consisting of the series connection of two parallel four-cell packs is shown in Figure 3. The research also seeks to determine whether more complex architectures would improve the battery performance (Jin and Shin, 2012; Kim, Shin, Chun & Cho, 2012; Ota, Sato & Akagi, 2016). A battery is powerful when it respects the mission profile imposed by the external load. That is to say, when it fulfils the mission without failure and ensures it for a long time. Typically, a battery reached its end of live when it is only able to store 80% of its capacity Q_0. The BMS determine the lifespan of the battery it drives.

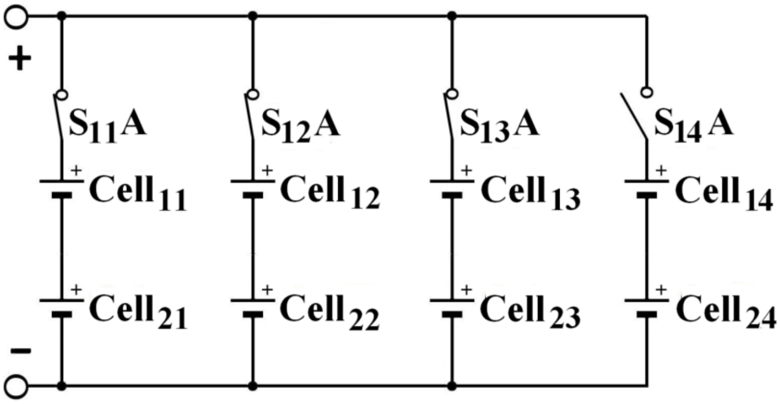

Figure 2. Example of two by four-cell SP architecture

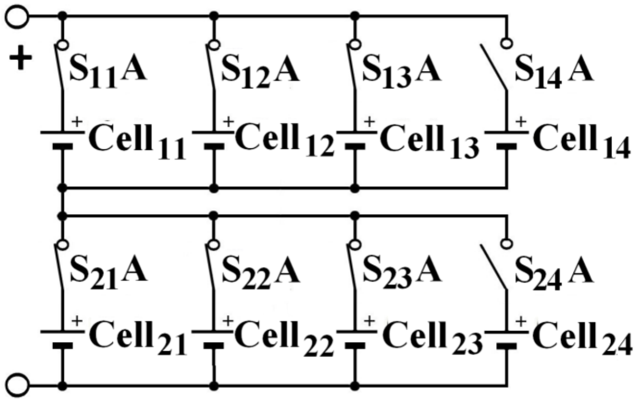

Figure 3. Example of two by four-cell PS architecture

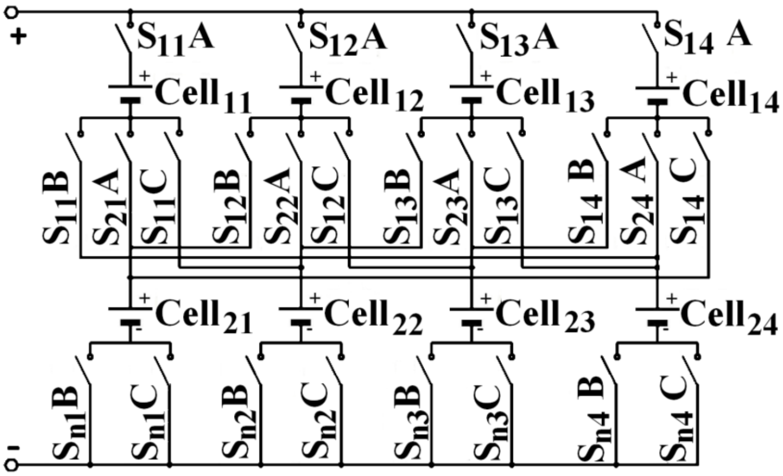

Figure 4. Example of two by four-cell C3C architecture.

The architectures presented in these papers all require adding a large number of switches, which can reduce the battery reliability. Among these, a solution minimises the number of switches at three per cell: the C3C architecture (Savard, Sari, Venet, Niel & Pietrac, 2016a; Savard, Venet, Pietrac, Niel & Sari, 2018a). An example of C3C (2, 4) comprising two rows of four cells is shown in Figure 4. Using an adapted optimisation algorithm (Savard, Venet, Niel, Pietac & Sari, 2018b), it is possible to improve by approximately 40% the battery operating time, regardless of the architecture chosen: SP, PS or C3C. In return, the battery would include a reduced number of redundant cells. This is to isolate the weakest cell (meaning the cells with the highest temperature, the highest charge when the battery is recharging or the lowest when the battery is discharging). The C3C architecture, due to the flexibility provided by the switches, is able to isolate a single cell, while the other architectures can only isolate a complete string of cells (SP architecture) or a complete row (PS architecture) (Savard et al., 2018b; Savard, Niel, Pietrac, Venet, Sari, 2016b).

Then the question is: what is the most efficient architecture in terms of management? That is, if the three solutions bring the same result in terms of lifespan, one of them made better use of the available resources (cells as staff and energy used to recharge the battery as an outside partner)? All the prerogatives of a managerial performance assessment by the EFQM grid are present: resource management (the cells), strategy use (optimisation algorithm), external partners (battery recharge), process (architecture), impacts on the customer (energy supplying to the external load) and on resources (the cell aging state at the end of mission). The first columns of Table 2 present the translation of the indicators in the case of the example studied in this paper, as well as the weighting of each criterion.

The cells impact criterion is composed of four indicators. The first two are based on BMS information from these sensors and the second two are internal indicators for evaluating performance, based on the calculation of cell state and state aging.

Table 2. EFQM indicators declination for battery monitoring and scores

Criterion/ indicator	Description	Weighting	PS architecture	SP architecture	C3C architecture
1	Leadership (the BMS)	7.50%	0.79	0.75	0.75
1a	The BMS is exemplary; it perfectly executes the tasks for which it is designed.		1	1	1
1b	Each possible situation, related to the coming external load requirement has been anticipated and the optimal solution has been implemented.		0.75	0.75	0.75
1c	The BMS monitors, evaluates and controls the system to improve performance (no failure, long lifespan).		1	0.75	1
1d	The BMS optimises the operation of each cell.		0.75	0.75	0.75
1e	The BMS ensures quality switching (switches opening and closing).		1	1	1
1f	The BMS controls the configuration changes without disturbing the service rendered (no micro-cut or voltage/current spikes).		0.25	0.25	0.00
2	Strategy	10.00%	0.60	0.65	0.70
2a	The control law is based on the knowledge of		0.75	0.75	1

	specifications and environment (temperature).				
2b	The control law integrates the BMS performance and its computing ability.		1	1	1
2c	The control law can be modified by the BMS.		0.25	0.25	0.25
2d	The effectiveness of the control law is measured.		0.50	0.75	0.50
2e	Operation in degraded mode (supply to the external load of a current lower than the specified current) is possible.		0.50	0.50	0.75
3	Cells	10.00%	0.85	0.85	0.95
3a	The state of each cell is taken into account for its control.		1	1	1
3b	There is homogeneity and fairness in the charges extracted during a discharge–recharge cycle.		0.75	0.75	1
3c	Each cell is used to store and provide energy.		0.75	0.75	1
3d	The weakened cells are put to rest.		1	1	1
3e	The cells cannot enter an insecurity zone (overload, deep discharge and high temperature).		0.75	0.75	0.75
4	Partnerships	7.50%	0.55	0.50	0.85
4a	Respect of the mission profile imposed by the external load both in discharge and recharge.		0.75	0.50	0.75
4b	All energy sent to the battery is used.		0.50	0.50	0.75
4c	The cell curative maintenance is easy (cells are easily replaceable).		0.75	0.75	0.75
4d	Curative maintenance does not introduce an electrical imbalance risk (inappropriate association of new and old cells (Abbas and Kim, 2018).		0.00	0.00	1
4e	The architecture is adapted to the control law.		0.75	0.75	1
5	Process	15.00%	0.75	0.88	0.92
5a	Metrology is designed to		1	1	1

	bring to the BMS the most relevant indicators.				
5b	The operational security tools deployed allow to improve the battery and the cell lifespans.		1	1	1
5c	The storage of energy is distributed among all the cells.		0.25	1	0.75
5d	The weakened cell isolation is reversible.		0.75	0.75	1
5e	Resource management follows an algorithm to improve performance.		0.75	0.75	0.75
5f	Redundant cells contribute to overall performance.		0.75	0.75	1
6	Customer results (external charge)	12.50%	0.50	0.50	0.50
6a	No fault or micro-clipping in power supplied to the external load.		0.25	0.25	0.25
6b	Existence of internal indicators to estimate compliance with the mission profile.		0.75	0.75	0.75
7	Results on cells	12.50%	0.50	0.56	0.75
7a	No disparities in the warm ups.		0.25	0.25	0.50
7b	Failures occur randomly, not only on certain cells.		0.25	0.50	0.75
7c	Existence and use of internal indicators to estimate the state of the cells.		0.75	0.75	0.75
7d	Homogeneity of cell aging.		0.75	0.75	1
8	Societal results	0.00%			
8a	Articles, reports and reviews on each of the solutions.				
8b	Number of applications using algorithm and architecture.				
9	Activity results	25.00%	1	1	1
9a	Measurement of effectiveness: lifespan gain, compared to a battery just meeting the needs (neither redundant cells nor optimisation algorithm).		1	1	1
9b	Measurement of		1	1	1

	efficiency: ratio between lifespan gain and deployed resource cost (number of switches and spare cells).			
	Global score	74	76	83

5. Results and discussion

The last columns of Table 2 present the detailed results of each indicator for the three studied architectures. Indicator thresholds should be interpreted according to the achievement level of each solution. For example, for the 1c indicator (how the BMS monitors, evaluates and controls the system to improve reliability performance and lifespan, the PS and C3C solutions get a score of 1 and the SP only 0.75). All the solutions evaluate the cell aging and act to isolate the weakest, which improves the lifespan, hence the score of 0.75. C3C and PS architecture reliability is better than the SP (Savard et al., 2016b).

Each area accounts for half of the overall assessment. Leadership and partnership (7.5%) account for half of the process criterion (15%). Strategy and cells have an intermediate weight (10%). The importance of each criterion should be valued by a different weighting of each. To evaluate the interest of using one or another architecture, the BMS and the external energy source are not discriminating points, while the deployed strategy and the resources using are important, as the resources use way is paramount. For the results area, the societal criterion has been neutralised because, to date, the literature on the comparison of battery architectures is not abundant enough. The economic result (25%) was weighted twice the value of the cell impact and external load criteria (12.5%) to reflect the importance of an accomplished mission.

The C3C architecture achieves better results for the strategy, cells, processes and, especially partnership criteria. Indeed, since this architecture allows to isolate any cell wherever it is physically located in the battery, it is actually possible to put at rest the weakest cell, whereas a SP architecture must isolate the whole cell string with the weak element and a PS architecture, a pack of cells in parallel. It, thus, makes it possible to better control the temperature rise consequences and a functioning in degraded mode (supply to the external load of a current lower than the specified current). For the same reason, it really makes it possible to use each cell according to its state of weakness and what the external load requires or provides power. In addition, for a C3C architecture, weakened cell isolation is reversible as long as the cell is rechargeable and all cells, including surplus cells, contribute to the mission equally. Finally, as all the cells are controllable one by one, all energy sent to the battery can be stored and restored. Especially, when the battery is fully charged, this implies that all cells without exception are fully charged. Indeed, in a cell string, the weakest cell charges the fastest. In SP architecture, it is necessary to add balancing circuits to prevent the charging stops, while the other cells are not recharged. The possible improvement levers result from the enablers area criteria. Intrinsically, the C3C architecture is difficult to more improve and brings a managerial performance clearly superior to other architectures. To achieve the same level of performance, it seems difficult, except to add switches in the SP and PS architectures to be able to control each cell. This is possible, but leads to the solutions already mentioned in the section devoted to the state of the art, for which the number of switches per cell is often greater than three.

The impact on each stakeholder can be deduced from the result area criteria. Here again, the C3C demonstrates its superiority, in particular, because the cell by cell control makes it possible to reduce the disparity appearing in the cell temperatures. Indeed, there is a thermal disparity due to the structure layout. As a result, the cell failure is mainly random and unrelated to their temperature. Finally, and this is perhaps the main advantage of the C3C architecture, at the battery life ending, all the cells have a similar aging (Shili, Hijazi, Sari, Lin-Shi & Venet, 2017b) and can then be more conveniently used in second life (Casals, Garcia & Canal, 2019; Garcia, Ganzalez-Benites & Casals, 2016). In SP and PS architectures, the cells present very important disparities in their aging, and therefore in their rest useful life potential.

The weak point of the C3C architecture comes from the many switch commutations, linked to configuration changes. The disturbance risks, such as micro-cuts, in the rendered service, are greater.

The comparison of the overall score answers the question of the most efficient architecture. The best performance in terms of the management is provided by the C3C. It is, therefore, undeniable that this architectural solution deserves to be studied in greater depth, by endeavouring to reduce the switching impacts, ensuring a sufficient reliability of the switches control and a reduction of parasitic phenomena, harming precise switching.

6. Conclusion

The EFQM analysis grid allows to determine an organisation managerial performance. Thus, weak points and improvement levers of an organisation can be identified. The method can be declined in any system, not necessarily with human being management if the system includes one or more strategies and a resource management. This is particularly the case within the BMS. Batteries are usually organised in SP or PS architectures. The research aims to define other architectures that would configure the cell (as resources) connections, due to switches, differently depending on the state, in which they are, and the external load needs. Among these, the C3C solution is the one that allows for a minimum of switches a multitude of possible configurations (Savard et al., 2017). However, it is not yet deployed. Applying an analysis with the EFQM criteria to the different battery architectures demonstrates that the C3C architecture is the most efficient in terms of the management. It optimises the energy stored, supplied and allows, because all cells age in the same way, an easy reuse them in the battery second life. Its weak point, identified by the indicator with the lowest score, is related to the large number of commutations and the possible consequences on the current delivered to the external load. It is mainly on this point that future research on the C3C architecture should be directed so that it can be deployed in industrial solutions.

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