Future of control and operations in the era of internet of things

Iiro Harjunkoski

Aalto University, School of Chemical Technology, Kemistintie 1, 02150 Espoo, Finland
ABB AG, Corporate Research Germany, Wallstadter Str. 59, 68526 Ladenburg, Germany
(Tel: +49(0)6203-716014; e-mail: iiro.harjunkoski@de.abb.com)

Abstract: Internet of things (IoT) is one of the main current buzzwords affecting the process automation. There are several scenarios on how this will change the control and operations in process and manufacturing industries. On the one hand, through a better connectivity information will be much easier available, which could result in more complex systems due to the increased scope. One the other hand, some scenarios speak for more distributed decision-making and simplicity where one naturally needs to also consider the optimality aspects. Nevertheless, it can be expected that the importance of optimization will increase and in this paper we discuss some aspects related to the challenges and changes that are triggered by IoT.

Keywords: Scheduling, control, optimization, process automation

1. INTRODUCTION

The traditional process control research has faced major developments from the early regulatory schemes. More and more intelligence is provided through e.g. Model Predictive Control (García et al., 1999) with its awareness and anticipation of future states and later capability to optimally embed more complex logics, e.g. switching between various control strategies through the application of binary decision variables. Perhaps even a more significant a change has been in moving process control related functions from the HW-controllers to a PC environment. Through the introduction of the enterprise-wide optimization concept (Grossmann, 2005) enabling the integration of the information and the decision-making among the various functions that comprise the supply chain of the company, it is evident that control and e.g. planning and scheduling can and should at least partially be considered jointly. There are several scientific contributions on the topic of integrating scheduling and control and a summary of the research directions is given e.g. in Baldea and Harjunkoski (2014). The problem gives rise to a mixed integer dynamic optimization (MIDO) problem (Allgor and Barton, 1999), which is untrivial to solve for larger problem instances. Other approaches seek ways to enhance existing modeling strategies. The most common ones are either to enlarge the scope of advanced process control, e.g. through the use of economic-MPC type of approach (Subramanian et al., 2012), or to take a top-down approach assuming that the process dynamics are handled as parameters in the scheduling models that can be updated regularly (Chu and You, 2012) through double feedback loops. The most successful use cases have been applied to continuous processes where the scheduling challenge (number of potential alternatives) is moderate and main value comes from optimal trajectories in changeovers e.g. in polymer production. The theoretical expectations are difficult to prove in practice and so far operations and control are still hierarchically separated in most industrial landscapes.

2. IMPACT OF INTERNET OF THINGS

With the recent developments towards internet of things (IoT), we can expect that in the future devices and systems can seamlessly communicate. The most typical IoT-effects are seen in data analytics, where new devices can on-line collect earlier hardly accessible information and feed it into the cloud, where theoretically "unlimited" computing power can be used for processing the data or optimizing larger-scale problems. Owing to mobility, the results are accessible anywhere and at any time. The impact on process control and other process operations is quite straightforward: They should become more integrated and collaborative and this is supported by the IT-structures. In many industrial visions, the traditional automation pyramid (see Fig. 1), structurally separating process control, scheduling and planning to their own hierarchical levels, has come to its end.

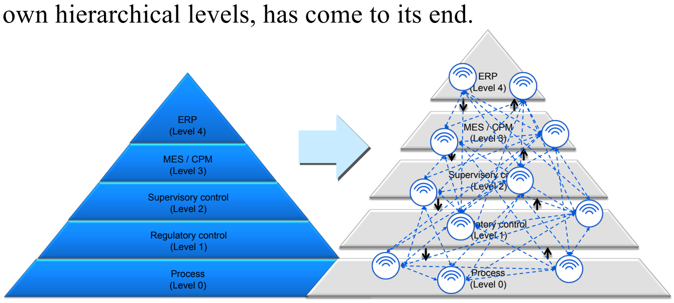

Fig. 1. Dissolving automation pyramid

The hosting levels 2-4 (all functions above regulatory control) may melt together into a single functional level, in which all data and information is available to any function in operational planning and execution. This calls for more collaborative methodologies and increases the role of software development. In the future, even a PID-controller can simply be an IoT-enabled actuator connected to any PC or mobile device.

As seen in Fig. 1, the earlier well-categorized functionalities that logically belonged to one larger solution bundle, such as manufacturing execution system (MES) transforms to a more flexible hierarchy (right side of Fig. 1). The circles represent well-connected functionalities that are in the future only logically mapped to the earlier levels of an automation pyramid based on their function. This directly realizes one of the goals of internet of things: All solutions can directly be connected to the internet/intranet and communicate and exchange data with each other. Thus, instead of having only a handful of connections between the bundled blocks or earlier hierarchical layers, now there are theoretically an unlimited number of communication channels, which opens up a communication challenge e.g. in scheduling. Here, in a typical case order-related information is retrieved from the business systems and the ongoing production is monitored through the control system layer. Nevertheless, the major functionalities do not disappear despite the fact that the established hierarchical structures are replaced by point-to-point communication but this transition also allows that new connections can be easily established between earlier practically isolated systems, for instance by bringing quality, energy and operational aspects closer to each other. In summary, instead of having large monolithic system components, smaller software solutions can contribute, which also makes it easier for "small players", i.e. companies who only provide a small functionality to enter the market. In the multitude of possible connection points and increasing number of players one the key challenges is to create more modular and flexible systems that enable seamless data communication and even can combine earlier separated business models. This ensures that new opportunities can be exploited. ExxonMobil has positioned its visions towards the future control architecture through a set of presentations (Forbes, 2016). Their vision states concretely that a future control system should be built of distributed control nodes (DCN) that are dedicated single-loop controller modules connected to a real-time data service bus. Furthermore, the operations platform should be open and use open-source software. This would enable a much easier revamping of level-1 controllers, which using the current DCS architecture philosophy is in their view both complex and expensive.

This means that the entire paradigm of operations and control may change due to a new IT-landscape. A natural question is of course which challenges are academic and which ones are topics that should purely be solved by the industrial vendors. It seems intuitive that this type of evolution cannot be done without close collaboration and therefore identifying future possibilities and limitations are clearly an academic questions, whereas the realization of the SW-platforms should be heavily be driven by the industry.

3. CURRENT TRENDS

The above introduction has already covered some upcoming trends and in this section some of these are further explored. The so called hypes or trends may not all be long-lived but they certainly also affect the expectations of the end users and may indirectly steer the developments of future operations and control. Also, at least for researchers it is always desired to challenge the current state-of-the-art and investigate the true potential of emerging technologies. Below some of the relevant trends for scheduling are briefly discussed.

- Internet of Things: As already discussed above, this is the enabler for cyber-physical systems, which is the core of for instance Industrie 4.0 (Germany) and Smart Manufacturing (US) activities. What it basically means is that any device can be connected to the internet allowing both way communications across- or between plants. This makes new data available also across operations and supports more horizontal applications with decentralized decision making. This fact easily creates unrealistic expectations through the countless opportunities of cross-collaborations between applications. A research question is to identify the main benefits from this collaboration potential. It is important that the engineering and information technology research communities collaborate on these to enable maximum flexibility, as it can result in a paradigm change within the process automation and its functional components.
- Automation Cloud enables software applications be installed not physically in the plant but anywhere through either intra- or internet connection. This enables the use of much more powerful computing resources (e.g. parallel computing) and easier remote administration. It can also allow purchasing a solution as a service without investing in hardware, thus reducing the investment risk. Technically, even if it is possible to solve larger mathematical problems using the "cloud" still only a few algorithms exist that fully takes advantage of this. Definitely, a research challenge is to identify how "unlimited" computing power may affect the life of a normal production facility and to define optimization algorithms that can fully benefit from this and create added value. Methods for systematically evaluating the true optimization potential of a processing plant are still missing. Note that a cloud solution can also be hosted locally.
- Big Data technologies aim at analyzing large sets of non-structured data. This can enable new knowledge about the production identifying problems early or creating more accurate data-driven models. For instance, a scheduling function within operations can become more aware and knowledgeable about the underlying and surrounding processes – or the control strategy can be automatically adapted to various situations. It is, nevertheless, most important to have an idea of what one is looking for.

- Smart Grids and Renewable Energy. These energy-related topics have increased the importance of energy for scheduling and control and opened a bi-directional information flow making it possible to adapt operational decisions to changing energy availability and pricing (industrial demand-side management). Also, new processes related to energy may become part of production planning. A challenge is to create efficient demand-side management solutions that explore the opportunities on all levels from process control to short-term planning.
- Mobility, Unmanned Sites and Remote Operations all contribute to more automated process operations and control. The main idea is to increase the safety of operations, reduce costs and be able to monitor and interact with the process from anywhere at any time. Upcoming standards e.g. 5G with very low latency should enable geographically distributed control solution components. In principle this could be seen as a pure IT-topic. However, not having operators at hand puts more responsibility on the automation and its optimization solutions, which must comprise some level of domain competence. This also raises the global perspective possibly leading to larger problem instances. In the long run some of the operator experience will be replaced, which requires fail-safe algorithms also in extreme situations. Furthermore, what kind of remote interaction is needed?
- Service, for instance software-as-a-service (SaaS), provides a large number of opportunities, where basically the imagination is the limit. Can this be a way to make control and operations solutions easier deployable or provide a performance-based solution where the end-customer pays related to the quality of the resulting production or the computational efforts? Will this drive the improvement of algorithms? A main challenge is related to value creation, i.e. how to measure the offered added value?

It is evident that fulfilling all of these aspects requires one or two decades of further developments. What it in any case shows is that the control and operations functions will have a central role also in a more automated and integrated industrial landscape. One of the main discussions will be around centralized or de-centralized approaches and how to in the best way utilize the unused computational capacity.

4. ACADEMIC CHALLENGES AND FUTURE DIRECTIONS

In general, the importance of operational and control functions will not diminish. On the contrary, the industrial need for new optimization schemes is growing (Harjunkoski, 2016). New arising communication technologies enables the collection and exchange of information in a much more detailed level creating many opportunities to include and consider a wider scope of aspects related to production. With the ever increasing availability of data and higher level of automation and electrification, e.g. production scheduling and process control cannot anymore be seen as autonomous solutions. The pressure to connect to and interact with neighboring solutions and systems is increasing (Engell and Harjunkoski, 2012). This makes it for instance very difficult to adapt partly manual, often rule-based decisions making to a larger scope due to the complexity of new interlinked goals and targets as well as theoretically unlimited opportunities. To increase the simplicity and define what actually makes sense, what brings additional value and is technically feasible is clearly also an academic challenge. Examples of this are the increasing research on industrial demand-side management taking advantage of the fluctuating price information of electricity (Mitra et al. 2014), as well as on integration of scheduling and control (Baldea and Harjunkoski, 2014).

In a similar fashion, integration to the supply chain level (e.g. Chu et al., 2015) is important for the overall operations in order to receive up-to-date commercial order information, including their priorities. All of the above areas of research should ensure, among others, that the provided schedule is aware of the surrounding environment as well as the underlying process. Figure 2 from Engell and Harjunkoski (2012) illustrates the various dependencies of today's hierarchical decision layers. One can observe that each level only communicates with the neighboring ones. With the future IoT concepts this should not be the case but rather all meaningful communication and communication channels should be enabled.

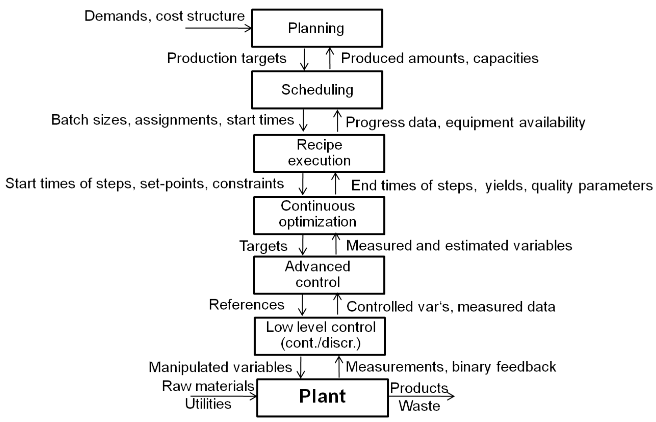

Fig. 2. Decision layers in operations – from supply chain to the process (Engell and Harjunkoski, 2012)

Some of the main challenges can be identified in the modeling and solution of the resulting multi-level problems. The first question is how to in the first place create a model of reality and what gets lost during this process? Applying e.g. mixed-integer linear programming (MILP) techniques for slower (static) problems limits the models to systems of linear equations. To date non-linear approaches to solve larger-scale MINLP-problems including numerous binary variables have been proven successful only in a few selected examples. Without going into details, other possible techniques to support larger problem instances are timed-automata, constraint programming and software agent based methods. Even if there are a number of promising approaches available, a major modeling challenge remains: If we want to optimize the overall operations, how should we model an objective function that captures the various aspects of the problem components? For instance, the most typical scheduling objective of minimizing the make span is not as easily measurable as for instance energy costs, which makes balancing of various objective function components untrivial. This is partly due to the difficulty of revealing the entire cost structure of companies, which often is a main trade secret.

Modeling becomes even harder a challenge when combining different optimization domains and dynamics: how to express the main decisions and limitations in a compact and balanced way such that different targets are simultaneously met? Bringing process dynamics and business objectives into one problem can easily lead to the fact that one part of the problem is biased and cannot even meet its minimum targets. In some cases intelligent problem decomposition, e.g. bi-level or Lagrangean decomposition can help reaching a global solution if enabled by the underlying problem structures. In scheduling, the representation of time is very important and for instance in industrial demand-side management, the process itself may need to be planned on a minute-level (process specific), whereas the electricity consumption only needs to be accounted for every 15 or 60 minutes (grid specific). Furthermore, ancillary services may need to be considered on a second basis. An essential question is if it is even in the first place possible to solve all these aspects together and, if not, would that imply going back to the old hierarchies? Thus, new modeling concepts are needed for combining the complex non-linear and non-convex models, which poses a main challenge to the solution algorithms as this often results in even larger models due to the need of auxiliary variables and constraints in linearization / convexification steps. In theory, most approaches allow combining or expanding the models to cover more problem aspects but the number of decisions to be optimized often increases significantly, for instance through a larger number of binary variables. To make problems also practically solvable, smarter modeling strategies are needed besides more efficient solution algorithms. Handling uncertainty is in general not yet deployable due to the fact that even the corresponding rigorous models do often not perform fast enough to satisfy industrial requirements. For instance, stochastic optimization is much more suitable to planning problems where also the impact of uncertainty can be much higher than in short-term problems. Furthermore, in short-term scheduling it is not trivial to identify and formulate the most "correct" scenarios, the goodness of which entirely defines the respective benefits. Thus, the most successful approach to handle uncertainty today is via rescheduling or control actions – or using some emerging technologies such as agent-based methods.

Apart from the modeling and solution challenges, one essential question is related to the SW-architecture of future automation systems. The future automation needs to allow more open interfaces for value-adding components and ideally provide one single data source that is shared among all players. Ensuring that the data exchange is based on established standards is essential in order to support the modularity, flexibility and interexchange-ability of system components. The definition of such standards must be done in a forward-looking manner ensuring that also the next generation technologies can be incorporated naturally. It is likely that distributed control systems (DCS) of today partly lose their roles as coordinating entities and the control and operations functions are partly redefined. Nevertheless, this will be a long process as companies are not willing to change their established and proven systems before there are clear indications of the potential benefits. Therefore, the main drivers for all changes should be safety, sustainability, profitability and ease-of-use.

To summarize, the collaboration and inventive contribution from the academia is crucial to tackle the practical challenges faced by the industry – today and tomorrow.

5. CONCLUSIONS

In the future, control and all levels of operations and operational planning must co-exist in the same environment, supplementing each other without redundancies or competitive functions. The future process control is synergistic process control, which benefits from other functions and information across entire process systems – and dilutes the borders between control and operations. This change will require cross-disciplinary collaboration between engineering domains and especially pose many challenges to the process systems engineering community, since despite more intelligent and capable systems, the engineering knowledge is going to play a key role in ensuring efficient, economic and safe process systems also in the future.

REFERENCES

Allgor R.J, Barton P.I. (1999). Mixed-integer dynamic optimization I: problem formulation, Computers & Chemical Engineering, 23, pp. 567–584.

Baldea M. and Harjunkoski I. (2014). Integrated production scheduling and process control: A systematic review, Computers & Chemical Engineering, 71, pp. 377-390

Chu Y. and You F. (2012). Integration of scheduling and control with online closed-loop implementation: fast computational strategy and a large-scale global optimization algorithm. Computers & Chemical Engineering, 47, pp. 248–268

Chu Y., You F., Wassick J.M. and Agarwal A. (2015), Integrated planning and scheduling under production uncertainties: Bi-level model formulation and hybrid solution method, Computers & Chemical Engineering, 72, pp. 255-272

Engell S. and Harjunkoski I. (2012). Optimal operation: Scheduling, advanced control and their integration. Computers & Chemical Engineering, 47, pp. 121-133

Forbes H. (2016). ExxonMobil's Quest for the Future of Process Automation, ARC Insights, ARC Advisory Group, April 26, 2016

García C.E., Prett D.M., Morari M. (1999). Model predictive control: Theory and practice—A survey. Automatica, Volume 25, Issue 3, pp. 335-348

Grossmann I.E. (2005). Enterprise-wide optimization: A new frontier in process systems engineering. AIChE Journal, Volume 51, Issue 7, pp. 1846–1857

Harjunkoski I. (2016). Deploying scheduling solutions in an industrial environment, Computers & Chemical Engineering, doi:10.1016/j.compchemeng.2016.03.029

Mitra S., Pinto J.M. and Grossmann I.E. (2014). Optimal multi-scale capacity planning for power-intensive continuous processes under time-sensitive electricity prices and demand uncertainty. Part I: Modeling. Computers & Chemical Engineering, 65, pp. 89-101

Subramanian K., Maravelias C.T. and Rawlings J.B. (2012). A state-space model for chemical production scheduling. Computers & Chemical Engineering, 47, pp. 97–110.