Autonomous Performance Monitoring of an On-Line Real-Time Decision Support System

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Abstract: Many manufacturing environments are only semi-automated and still require operator input for key aspects of operations. Decision Support Systems (DSS) are a useful means of improving the performance of human-in-the-loop control aspects of operations. Passive DSS systems can empower operators to make optimal decisions while still allowing them to retain control of the plant. However in practice DSS systems are not always utilised to their full potential and ‘operator discretion’ can result in sub-optimal plant performance.

An on-line real-time DSS has been implemented to help operators minimise redundant cleaning cycles in a brewery. Autonomous monitoring functionality has been developed to provide visibility and transparency of the actual use and performance of the DSS.

Keywords: Decision support systems, Industry automation, Industrial control, Information systems, Manufacturing

1. INTRODUCTION

For many industries there are aspects of operations that are difficult to automate because they rely on human input and decision making. The reasons are many and can range from cost through to a dynamic or rapidly changing solution-space of high dimensionality.

For a subset of these scenarios an effective solution can include the use of a Decision Support System (DSS) that presents a machine’s best estimate for a solution or decision but still requires the final control action or decision to be made by a human. An on-line real-time DSS has been developed to help operators to minimise redundant cleaning cycles in a brewery.

The Carlton & United Breweries (CUB) plant at Yatala, in Queensland Australia, is a relatively modern plant with a capacity of 540 million litres per year. The plant has had a strong focus on energy management almost since its construction in 1988. It is an efficient plant and has been regarded as being at or near world’s best practice for energy and water consumption for some time (Putman (2006) and Foxall et al. (2008)).

It has an advanced G2-based Utilities Management System (UMS) that operates on the plant’s extensive integrated automation and control system. In an attempt to further reduce waste from the brewery’s cleaning cycles an operator DSS was developed to assist with vessel selection (Lees et al. (2009)).

The aim of this research was to develop information infrastructures that autonomously measure the use, and hence overall performance, of the operator DSS.

It is commonplace for plant automation and automatic control systems to contain performance monitoring functionality. However higher-level systems for operations management often involve human-in-the-loop components. Many aspects of operations involving higher-level systems have a significant impact on plant efficiency and environmental impact. However they are not always accompanied by the equivalent performance monitoring functionality of their automatic control counterparts.

The system architecture of both the underlying UMS as well as the DSS is described. A brief overview of the pertinent aspects of the cleaning requirements of the brewery is included to provide sufficient domain knowledge to facilitate an understanding of the DSS. The key design aspects and functionality of the DSS is provided along with those of the performance monitoring system. Actual results are included demonstrating both the level of use of the DSS itself as well as the ability of the monitoring system to provide visibility of performance information.
2. DECISION SUPPORT SYSTEMS

The term Decision Support System (DSS) is used in reference to a broad category of information systems that are intended to assist humans in the decision making process. Decision support research can be traced back to the early 1960’s (Power (2004) and Bhargava et al. (2007)). Other terms, such as Expert System, Intelligent System and Knowledge-Based System are commonly used in reference to particular types of DSS (Power (1997)).

A significant portion of DSS’s are designed to provide a means of access to embedded expertise. They have proven to be particularly useful in applications that require problem solving or complex decision making. Some of the common benefits of DSS’s include consistent responses or behaviour, which can lead to improved efficiencies (Shim et al. (2002)) and effectiveness of staff.

The core concerns of manufacturing operations are usually centred around parameters such as quality, productivity and production costs. Although concerns such as sustainability and energy management also have an impact on production costs they are often of secondary concern. DSS’s can be used to empower operators to run a plant in an energy efficient manner without detracting from their core focus.

3. DSS APPLICATION: VESSEL SELECTION IN A BREWERY

A DSS has been developed to reduce the environmental impact of cleaning operations within a modern brewery. Fermenter vessels are required to receive wort (fermentable liquid extract) from the brewhouse in preparation for the fermentation process. Prior to the transfer of wort, the operators are required to select an appropriate sized fermenter. The act of selecting the vessel has no impact on product quality or productivity but it does have an impact on sustainability. The optimal vessel for selection changes over time and is a function of a number of variables including the plant state, making this an ideal application for an on-line DSS.

4. CLEANING REQUIREMENTS IN A BREWERY

It is important that beer is processed and stored in a clean and microbe-free/sterile environment. In a non-sterile environment, bacteria, microbes and wild yeasts can flourish and cause beer spoilage. Bacteria and wild yeasts can affect both the physical and flavour stability of beer. The consequences can be costly and can include product that is not fit for sale. Over time a build-up of product residue on equipment surfaces can also have an impact on the plant performance (e.g. the performance of heat exchangers).

Hence the pipe-work, vessels and any surfaces that come into contact with the product need to be frequently cleaned. Cleaning cycles usually include the use of strong detergents in-between rinse cycles. A range of strong detergents are used including Alakali’s Caustic Soda (2% NaOH) and acids (O’Rourke (2003)).

4.1 Automated cleaning and CIP systems

Modern breweries have dedicated Clean-In-Place (CIP) plant for automated cleaning. The CIP philosophy (of automatically cleaning the plant without disassembly) is used to improve the consistency and quality of cleaning. The use of automated CIP sets also improves plant efficiency and maximises vessel availability.

The Yatala brewery has over 15 independent CIP sets that service the entire site (including all vessels, piping and packaging lines). Collectively these CIP sets run over 236 different CIP cycles.

In many respects the brewing process is basically a sequenced array of batch operations. That is, a sequence of cleaning cycles interleaved among a sequence of brewing/product related batch operations.

The dimensionality of the cleaning operations across the Yatala brewery is quite high, with 15 CIP sets running over 236 different cleaning cycles to clean over 195 different vessels and a number of transfer and packaging lines.

4.2 The environmental impact of CIP

Even though the brewery’s primary output is beer, the cleaning operations are responsible for a significant portion of the plant’s environmental footprint. In a given month the brewery might produce around 260 brews. However in such a month the plant would typically run over 2,300 CIP cycles to support those brews through the process.

Some of the ways in which CIP operations have an impact on the environment include:

- Carbon emissions (Detergents): The production of detergents by suppliers and its delivery to site both incur carbon emissions.
- Salt balance in environment: The combination of acidic and alkaline detergents (and beer & alkaline additives) usually react to form salt compounds. Hence there will be a salt impact at the local municipal treatment plant.
- Water consumption
- Carbon emissions (CIP plant): Electricity is required for pumping detergents, gas is required for heating detergents and water
- Additives: Various additives, such as surfactants, are also used in cleaning cycles. Although they are used in much smaller quantities than detergents they also contribute to carbon emissions and environmental impact.

Cleaning operations make a significant contribution to the environmental footprint of a brewery. Both the individual CIP cycles and sets should be optimised. This would include the physical equipment as well as the control philosophy. Each cycle should be tuned to ensure that it consumes the minimal amount of detergent and water that are required to perform the task (Lees et al. (2009)). Another important consideration is to ensure that only the minimum number of CIP cycles are used. The goal of the DSS described in this paper is to identify and reduce/eliminate any redundant cleaning cycles.
5. DSS DESIGN AND FUNCTIONALITY

5.1 System objectives

The objective of the DSS is to provide recommendations for vessel selection that will result in minimal environmental impact while not affecting product quality or plant productivity. More specifically the aim is to identify and help minimise the occurrence of redundant cleaning cycles. Prior to the introduction of the DSS, operators would arbitrarily select vessels (within the required size category) for use. They would also arbitrarily select empty vessels for cleaning with little regard for the cleaning history or requirements of the vessel. This resulted in a significant number of cleaning cycles that could have been avoided.

In the context of a brewery, the proposed DSS is applicable anywhere where:

- There are multiple vessels/tanks to select from
- The tanks need to be cleaned and maintained in a sanitary condition prior to use
- An operator has to make a decision as to the sequence of vessel selection

There are three major areas at the Yatala brewery that meet these requirements. The six fermentation cellars that collectively contain 54 vessels; the 5 storage cellars that collectively contain 54 storage tanks and the 3 Bright beer cellars that collectively contain 32 bright beer tanks. However this research has focussed on the use of DSS for the fermentation area.

To ensure consistency of operation and to maintain product quality, breweries often develop a set of business rules that specify the requirements, terms, conditions and procedures of cleaning activities for each area of the plant. The business rules are typically the result of testing and measurement programs that determine the minimal requirements to clean and maintain plant equipment in a microbe-free/sterile state ready for use.

Business rules are often specifically tailored to the requirements of each area of a plant. The relevant business rules for cleaning operations in the fermentation area are:

1. CIP: A fermenter must undergo a full CIP cycle immediately following a fermentation cycle. A fermenter should not ordinarily require another CIP cycle until it has been used again (i.e., after the next fermentation cycle).

2. Sanitise: Once a fermenter has undergone a CIP cycle, it is available for use for up to 24 hours. If a CIP’d fermenter has been empty for a period of 24 hours or more then it must undergo a Sanitise cycle prior to use. (A sanitise cycle uses less chemicals and has a significantly lower environmental footprint than a CIP cycle.)

3. De-stone: Each fermenter is scheduled to undergo a de-stone cycle approximately every six months. The de-stone cycle includes the use of acidic detergents to remove any build up of calcium oxylate scale (beer stone) from the inside walls of the vessel.

Fig. 1. DSS system topology illustrating the major logical functions between the plant and the users

5.2 System Architecture

The topology of the DSS is illustrated in Fig. 1. At the time of printing the automation infrastructure at the Yatala brewery is predominantly based on equipment from Rockwell Automation. A number of PLCs (predominantly ControlLogix®) control the plant over a number of data networks (including Ethernet, ControlNet®, DeviceNet® and Data Highway Plus (DH+)®). Operators interact with the plant (via the PLCs) over the RSView SE® Human Machine Interface (HMI).

The G2® real-time intelligent system platform was selected as the platform upon which the plant Utilities Management System (UMS) would be developed (Lees et al. (2008)). It is a graphical object-oriented real-time rapid application development environment. It also has excellent connectivity with plant controllers, databases and third-party applications.

The UMS is an on-line real-time application with an array of modules that support various aspects of operations including: energy management, advanced monitoring, abnormal situation management, intelligent diagnostics, automated reporting and decision support (Lees et al. (2008)). The DSS exists as a module within the UMS, and hence also operates on top of the G2® real-time intelligent system platform. It communicates with the required plant controllers via OPC1 across an array of Data Servers (bridges). This enables the Data Model (of the fermenters) to mirror the actual plant state in real-time. The DSS model, having access to the live data model, is then able to provide decision support, run logging and automated reporting and decision support.

1 OPC is a data connectivity standard used in automation.
Fig. 2. Operator interaction pathways with both the HMI (for plant control) and the DSS (for optimal recommendation)

analysis functionality. Information is stored in an adjoining MySQL® database and is accessible using web browsers (via a Tomcat® web server).

5.3 DSS Functional Architecture

At the core of the DSS is a priority queue system that assists operators with vessel selection (as shown in Table 1). Computation of the priority queues is based on a combination of the current state of the vessels and the business rules for cleaning operations in the fermentation area (as listed earlier in Section 5).

The DSS presents four individual priority queues for the operators; one for each required size/brew-count combination. For the scenario depicted in Table 1: if the operator is able to select vessel FTD02 within the next 8 hours and 12 minutes then an entire sanitise cycle can be saved.

The operator interaction with the DSS is depicted in Fig. 2. The DSS is a true ‘support system’ and as such it is not an essential component of the operator’s workflow, as they are able to control the plant without it. For plant control, the operators interact with the HMI server. However for optimal vessel selection, they monitor the priority queues that are presented by the DSS and follow the recommendations when making the selections via the HMI client. While the HMI and DSS systems are currently segregated (above the PLC), there are no technical barriers to increasing the level of integration in the future.

The DSS as a whole, is more than just the priority queue for vessel selection. The broader set of functionality that is encompassed by the DSS is presented in Fig. 3.

The live/real-time data is intended for use by operators for the purpose of influencing plant control decisions. There are two parts to the Historical data interface: Counts and Performance monitoring. The Counts interface provides management with a detailed record of the counts of the three types of cleaning cycles (CIP, sanitise and de-stone). The Counts interfaces are hierarchical and provide visibility by plant area (such as fermentation), cellar and individual vessels.

The Performance monitoring functionality enables management to monitor the operator’s use of the DSS.

Fig. 3. DSS functional architecture

6. DSS PERFORMANCE MONITORING

Operator acceptance and adoption are always of concern when introducing new systems into a manufacturing environment. During the design of the DSS, significant focus was placed on incorporating autonomous performance monitoring functionality. A conceptual depiction of the performance monitoring component is presented in Fig. 4.

The DSS and operators together form part of the control system to minimise redundant cleaning cycles. The
combination of the DSS performance monitoring module and management are part of a higher-level feedback loop whose purpose is to tune and improve the performance of the vessel selection function.

The key requirements of the performance monitoring functionality include:

- **Autonomous operation**: The monitoring, data collection, reporting & summary information and notifications must all operate autonomously without human assistance with either data entry or triggering.
- **Accurate**: It has to provide an accurate representation of the operation of the DSS.
- **Transparent**: While high-level metrics are useful, it is still necessary to be able to drill-down to monitor the performance of individual cellars and vessels.

There are four main components to the performance monitoring module, as depicted in Fig. 3.

1. **Adjacent cleaning cycles**: Provides a count of redundant (adjacent) CIP cycles.
2. **Vessel selection assessment**: Presents a count of the number of times a DSS recommendation was not used (i.e., the number of times that a selected vessel was not at the top of the priority queue).
3. **Vessel selection adherence**: Reveals what the queue priorities of the selected vessels were at the time of selection. Data for a twelve-month period is presented in Table 2. The intention for this view is that it will provide greater detail into user problems and usage patterns of the DSS.
4. **Vessel selection log**: The vessel selection log provides a precise record of the details of each vessel selection decision, in the context of the relevant plant state at the time. An example is presented in Table 3 showing: the selected vessels & the priority of the selected vessels against the top priority vessels that should have been selected. In run 13419 the DSS was recommending vessel FTF05. However the operator selected FTF01, which was only third in the queue at the time.

Most of the performance monitoring functionality is hierarchical and supports drill-down to also provide visibility by cellar and vessel.

In conjunction with the automated summary information, the DSS also distributes automated weekly email reports that push performance information to the relevant managers.

### Table 1. Decision support system: priority queues for fermenter selection

<table>
<thead>
<tr>
<th>Small Fermenters</th>
<th>Mid Fermenters</th>
<th>Mid Fermenters</th>
<th>Large Fermenters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Brew (A Cellar)</td>
<td>2 Brew (C,D,E,F Cellars)</td>
<td>3 Brew (FTG01)</td>
<td>4 Brew (A Cellar)</td>
</tr>
<tr>
<td>Vessel</td>
<td>Count</td>
<td>Vessel</td>
<td>Count</td>
</tr>
<tr>
<td>FTA02</td>
<td>2:23</td>
<td>FTF07</td>
<td>0:14</td>
</tr>
<tr>
<td>FTA05</td>
<td>5:19</td>
<td>FTE03</td>
<td>1:37</td>
</tr>
<tr>
<td>FTA15</td>
<td>12:20</td>
<td>FTC01</td>
<td>5:19</td>
</tr>
</tbody>
</table>

### Table 2. Fermenter vessel-selection queue adherence

<table>
<thead>
<tr>
<th>Queue position of selected vessel</th>
<th>Month</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>≥10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 2010</td>
<td>78</td>
<td>16</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5 2010</td>
<td>75</td>
<td>21</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>4 2010</td>
<td>71</td>
<td>17</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>3 2010</td>
<td>91</td>
<td>14</td>
<td>8</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>2 2010</td>
<td>92</td>
<td>10</td>
<td>10</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1 2010</td>
<td>77</td>
<td>21</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td></td>
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<tr>
<td>7</td>
<td>12 2009</td>
<td>100</td>
<td>21</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>11 2009</td>
<td>113</td>
<td>10</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>10 2009</td>
<td>106</td>
<td>21</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>9 2009</td>
<td>89</td>
<td>23</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>8 2009</td>
<td>66</td>
<td>16</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>7 2009</td>
<td>81</td>
<td>14</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3. An example segment of the Vessel selection log (timestamp values have only been withheld for space reasons)

<table>
<thead>
<tr>
<th>Run ID</th>
<th>Start Time</th>
<th>Selected Vessel</th>
<th>Priority</th>
<th>Top priority Vessel</th>
</tr>
</thead>
<tbody>
<tr>
<td>13423</td>
<td>(timestamp)</td>
<td>FTF07</td>
<td>1</td>
<td>FTF07</td>
</tr>
<tr>
<td>13422</td>
<td>(timestamp)</td>
<td>FTF01</td>
<td>2</td>
<td>FTF03</td>
</tr>
<tr>
<td>13421</td>
<td>(timestamp)</td>
<td>FTF04</td>
<td>1</td>
<td>FTF04</td>
</tr>
<tr>
<td>13420</td>
<td>(timestamp)</td>
<td>FTF06</td>
<td>1</td>
<td>FTF06</td>
</tr>
<tr>
<td>13419</td>
<td>(timestamp)</td>
<td>FTF01</td>
<td>3</td>
<td>FTF05</td>
</tr>
<tr>
<td>13418</td>
<td>(timestamp)</td>
<td>FTF15</td>
<td>1</td>
<td>FTF15</td>
</tr>
</tbody>
</table>

### 7. RESULTS

#### 7.1 DSS performance

During the twelve-month period represented in Table 2, a total of 1,404 fermenter-vessel selections were made. Clearly the current performance (i.e., level of use) of the DSS itself is reasonably low with only 73.6% of these selections lining up with DSS recommendations. While the operators are expected to check the DSS recommendations when selecting a vessel, this does not always occur. While 100% adherence may be theoretically achievable, in practice there will always be a number of abnormal situations and unexpected conditions that will require operators to not accept a recommended vessel. Indeed, this is the reason why there is still a human-in-the-loop for this function.

Plant management are currently developing a training program to increase the operator’s understanding and adoption of the DSS.

2 For example, activities such as new product development may require a specific vessel.
7.2 Performance of the Autonomous Monitoring System

The automated monitoring functionality has successfully highlighted that there is an issue with current levels of adoption of the DSS by operators. Its tight integration with the DSS and plant control system removes the potential for subjective bias or reliability issues that may otherwise be present in monitoring systems with human-based data entry. The hierarchical presentation of data facilitates drill-down to expose performance of individual vessels.

Perhaps most importantly, the ability of the system to record each vessel selection decision and the relevant plant state at the time of each decision have been instrumental in both system tuning and validating assertions of lack of operator attention to recommendations.

However it is also interesting to note the lack of visibility of causality with the vessel selections. It is possible for operators to coincidently select a vessel that is at the top of a queue without them actually using the DSS. Such a scenario is not of major concern as the real objective is to minimise environmental impact.

9. CONCLUSION

As the drive to further improve the energy efficiency of manufacturing plants continues, the focus will inevitably expand to encompass the significant impact that humans have on operational efficiency.

A DSS has been developed, at CUB’s Yatala brewery in Australia, to empower operators to make optimal vessel-selection decisions that will minimise the required cleaning cycles and chemical load on the environment. An autonomous performance monitoring module was also developed alongside the DSS and has successfully revealed the under-utilisation of the DSS by the operators.

This research has highlighted the importance of autonomous performance monitoring systems, especially for aspects of manufacturing operations whose effectiveness is dependant on human-in-the-loop performance. Autonomous performance monitoring provides a sustainable method of ensuring that operator-based DSS systems continue to have the intended impact.

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