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Utilising a hybrid DMAIC/TAM model to optimise annual maintenance shutdown performance in the dairy industry: a case study

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Abstract

Purpose – Output from the Irish Dairy Industry has grown rapidly since the abolition of quotas in 2015, with processors investing heavily in capacity expansion to deal with the extra milk volumes. Further capacity gains may be achieved by extending the processing season into the winter, a key enabler for which being the reduction of duration of the winter maintenance overhaul period. This paper aims to investigate if Lean Six Sigma tools and techniques can be used to enhance operational maintenance performance, thereby releasing additional processing capacity.

Design/methodology/approach – Combining the Six-Sigma Define, Measure, Analyse, Improve, Control (DMAIC) methodology and the structured approach of Turnaround Maintenance (TAM) widely used in process industries creates a novel hybrid model that promises substantial improvement in maintenance overhaul execution. This paper presents a case study applying the DMAIC/TAM model to Ireland's largest dairy processing site to optimise the annual maintenance shutdown. The objective was to deliver a 30% reduction in the duration of the overhaul, enabling an extension of the processing season.

Findings – Application of the DMAIC/TAM hybrid resulted in process enhancements, employee engagement and a clear roadmap for the operations team. Project goals were delivered, and original objectives exceeded, resulting in €8.9m additional value to the business and a reduction of 36% in the duration of the overhaul.

Practical implications – The results demonstrate that the model provides a structure that promotes systematic working and a continuous improvement focus that can have substantial benefits for wider

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industry. Opportunities for further model refinement were identified and will enhance performance in subsequent overhauls.

Originality/value – To the best of the authors' knowledge, this is the first time that the structure and tools of DMAIC and TAM have been combined into a hybrid methodology and applied in an Irish industrial setting.

Keywords Irish dairy industry, Maintenance overhaul, DMAIC, Turnaround maintenance, Operational effectiveness

Paper type Research paper

Abbreviations

AI = Artificial Intelligence;
AHP = Analytic hierarchy process;
BOMs = Bills of Materials;
CAPEX = Capital Expenditure;
CBM = Condition Based Maintenance;
CMMS = Computerised Maintenance Management System;
CSF = Critical Success Factors;
DMAIC = Define, Measure, Analyse, Improve, Control;
FMEA = Failure Modes and Effects Analysis;
KPI = Key Performance Indicators;
LSS = Lean Six Sigma;
MAMF = Mechanical Automation and Maintenance Fitter;
MCDM = Multi-Criteria Decision Making;
MTBF = Mean Time Between Failures;
OEM = Original Equipment Manufacturer;
OPS = Operations;
PDCA = Plan Do Check Act (Deming Cycle);
REM = Review Existing Maintenance;
SIPOC = Suppliers, Inputs, Process, Outputs, Customers;
TAM = Turnaround Maintenance;
TPM = Total Productive Maintenance;
TQM = Total Quality Management;
VOC = Voice of the Customer; and
WBS = Work Breakdown Structure.

1. Introduction

The Irish dairy industry is approaching crossroads having undergone significant growth in production output since the abolition of milk quotas in 2015, demonstrating the highest national growth rate of all European Union (EU) countries (Cele *et al.*, 2022). The industry now faces new challenges around its ability to process peak milk volumes in the spring yet to keep its capital-intensive plant employed gainfully and profitably over the quieter periods at the start and end of the milking season (Geary *et al.*, 2012). Few traditional manufacturing sectors have demonstrated similar growth in such a short space of time. Milk production output has increased by a massive 55% since quotas were abolished in 2015, (Ramsbottom *et al.*, 2020) with national volumes growing from 5.6 billion litres in 2014 to 8.8 billion litres in 2021 (CSO, 2022).

The Irish dairy season is based around early spring calving to maximise milk production in alignment with the grass growing season of March to October (O'Brien *et al.*, 2022).

Ireland's temperate climate lends itself to growing grass and this is the foundation of Ireland's lower cost of production and one of the key strengths of the Irish dairy industry (Timlin *et al.*, 2021). Traditionally farmers dry off their herds in November when the grass is in short supply and prepare for calving (Hennessy and O'Brien, 2017). During this natural window large processing facilities typically shut down and use the break to complete essential maintenance on their plant and equipment. This maintenance or "Overhaul" during the off season (Arthur, 2004) addresses any operational issues experienced during the year and completes statutory testing and quality inspections on plant otherwise unavailable during the production season.

In developing strategies to manage changes to their traditional overhaul, the dairy industry must look at what approaches, tools and techniques are used by other industries who face similar challenges maximising production plant availability (Arslankaya and Atay, 2015). The main quality management tool is total quality management (TQM) that helps dairies with the better understanding and quality control of the entire production process (van der Spiegel and Ziggers, 1999). The limitation of TQM use is the necessity to improve the knowledge of quality and methodologies concurrently with the rapid changes in the TQM's definition (Pyzdek, 2003). Lean Six Sigma (LSS) were used as continuous and breakthrough improvement tools to reduce variation in a dairy sector (Andersson *et al.*, 2006). LSS tools were integrated into dairy manufacturing due to the necessity to deal with simultaneous operations and systems which have a number of complicating characteristics, often unheard of in other industries (Powell *et al.*, 2017). The new quality management strategies and approaches are of interest to investigate due to the continued growth of Ireland's milk output that has put increasing pressure on producers to extend the processing season (Läpple *et al.*, 2012) and reduce the annual downtime requirement.

Farmers are incentivised to calf outside the traditional window to offset their production profile and ensure "year round" milk availability for processing (Geary *et al.*, 2014). The challenge now for producers is to somehow execute the annual maintenance overhaul in an ever-reducing window. Turnaround maintenance (TAM) (Ben-Daya *et al.*, 2009) is the mainstay of the oil, gas, and chemical processing industries. It involves extensive planning and preparation for maintenance and plant enhancement activities during a scheduled downtime event (Pokharel and Jiao, 2008). These process industries cannot afford to be down for long and strive for the day when shutdowns for maintenance are avoidable (Lenahan, 2006), so effective management of shutdown events are key and offer potential benefits and learning opportunities for the Irish dairy industry. Compared to the total productive maintenance (TPM) model that is implemented to achieve quality in maintenance engineering activities, TAM requires the best planning, scheduling techniques and highly qualified and skilled based personnel (Ahuja and Khamba, 2008).

The four key phases of TAM have been outlined by many practitioners (Ben-Daya *et al.*, 2009) and (Lenahan, 2006), are *Initiation, Preparation, Execution and Termination*. Details of the constituent elements of each phase have been described by several authors (Brown, 2004; Levitt, 2004; Rouf *et al.*, 1999) and can be summarised as follows; *Initiation* involves scope setting and organisation, *Preparation* includes planning and focuses on work breakdown structures, material sourcing and allocation of resources, *Execution* is the systematic completion of the physical work involved, as per the agreed schedule, finally *Termination* is the handing back of the plant, start-up and analysis of data gained from the turnaround activity. No published sources could be found on the application of TAM to the dairy industry, as it is primarily applied in Oil & Gas and chemical processing industries, but its success in these industries highlight its potential to deliver benefits to the dairy sector if a suitable vehicle for delivery can be developed (Ben-Daya *et al.*, 2009).

Six-Sigma's Define-Measure-Analyse-Improve-Control (DMAIC) process closely parallels best practice project "Life Cycle" management (Evans and Lindsay, 2015) and is in widespread use across industry to manage continuous improvement projects and activities, the methodology is at the core of six sigma (Knowles, 2011). Its application in dairy and food processing industries is not as well documented as in discrete manufacturing applications (Powell *et al.*, 2017). At its core, DMAIC is a structured approach to application of Six Sigma tools in the workplace (Brassard *et al.*, 2002). There is a clear suite of tools to be used at each of the five stages in the process to assist with problem resolution or process improvement (de Mast and Lokkerbol, 2012). An alternative LSS approach that is particularly suited when designing or redesigning a product or process is DMADV or Define-Measure-Analyse-Design-Verify (Kumaraendran and Rosmaini, 2022; Trubetskaya and Muellers, 2021). It is not as widely used in industry as DMAIC probably due to the fact that most industrial applications of LSS focus on quality improvement and defect reduction on existing products and processes as opposed to new or redesign of the complete process (Trubetskaya *et al.*, 2023).

The hybrid LSS methods were rarely used in previous dairy studies. However, the DMAIC-TPM hybrid model was used to achieve high process performance and overall equipment effectiveness in manufacturing industry (Antosz *et al.*, 2022). Despite the DMAIC-TPM model provided a good framework and methodology to improve the maintenance performance continually, the actions implemented in one company were difficult to use in modelling of total maintenance in other industries requiring more data and future model validation. Another DMAIC-TPM model was used in the manufacturing where TPM tools were integrated as a part of DMAIC Improve stage that includes failure modes and effects analysis, cause and effect analysis and mean time between failures analysis (Kumar Sharma and Gopal Sharma, 2014). The clothing and textile industries integrated DMAIC phases with the Plan Do Check Act cycle to improve the overall process efficiency as a part of the neural network model (Nedra *et al.*, 2019; Elboq *et al.*, 2020). Other studies combined the multi-criteria decision making (MCDM) methods such as Delphi method with the Lean models (Vinodh and Kumar Chintha, 2011). Analytic hierarchy process (AHP) methodology was integrated with lean assessment techniques to propose a road map (Almomani *et al.*, 2014; Ravikumar *et al.*, 2015; Bayazit, 2005). The hybrid models of MCDM and LSS domains were realised. MCDM tools were also integrated with AHP to facilitate lean assessment evaluation and to discuss the potential barriers aiming to provide accurate solutions as a part of AI network (Hosseini Nasab *et al.*, 2012; Wong *et al.*, 2014; Yadav *et al.*, 2018). While there are extensive papers written on hybrid models, there is little data available on the opportunities of combining several LSS approaches to evaluate the process optimisation, waste elimination, automatisation aiming continuously to improve the dairy plant operation in maintenance overhaul execution phase.

The purpose of this Case-based research is to combine DMAIC and TAM in a hybrid model and to apply it as a case study at Irish largest dairy processing site to optimise its annual maintenance overhaul shutdown, delivering substantial additional value to the business by extending the traditional production processing season. The research questions being considered in this study are as follows:

RQ1. How can LSS DMAIC tools and techniques and turnaround maintenance (TAM) elements be combined to create a hybrid maintenance overhaul delivery methodology?

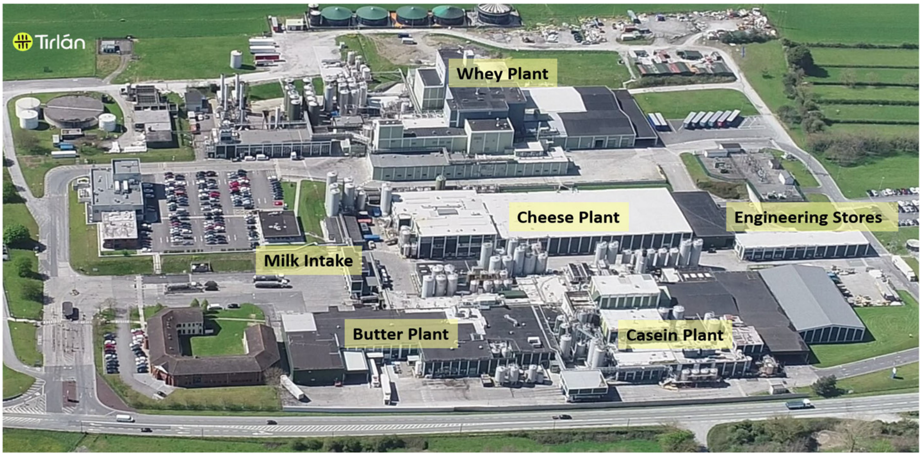
RQ2. Can this hybrid model be successfully applied to the largest processing site in the Irish dairy sector to improve their maintenance overhaul performance?

What follows in Section 2 is the detailed methodology that will be applied during this project-based study. Section 3 will outline the project results which will then be discussed in Section 4 and the conclusions arising from the research activity are contained in Section 5.

2. Methodology

This research aims to reduce waste, improve automatisation and process efficiency operations of the dairy plant during the overhaul maintenance period that requires the combined use of Lean Six Sigma DMAIC model with the key data from the Turnaround Maintenance (TAM) process through the establishment of a hybrid DMAIC-TAM model. The dairy industries regularly perform the maintenance of some equipment during the normal operation of plant using preventive, corrective, and predictive strategies. However, there are critical pieces of the equipment which cannot be inspected and maintained during the normal operation of plants unless facilities are totally shut downed to conduct the TAM event to overcome failures, which may cause high risks during the operation periods. Thus, TAM is performed during a certain period at every few years including the largest maintenance activities in dairy plants in terms of time and cost appearing as the main execution approach at Ballyragget processing site in Ireland (Figure 1). The DMAIC model was selected as the main structure for the research project because its focus is very much on process improvement, combining the improvement methodology with the structured execution approach of the turnaround maintenance (TAM). This resulted in the hybrid methodology that enabled both process improvement and transactional execution elements of the maintenance activity.

This novel methodology will be used in an Irish processing site to manage and optimise its annual maintenance overhaul. The case study is the largest dairy site in Europe processing approximately 1.3 billion litres of milk annually. Three distinct factories are contained on site, the first contains Milk Intake, a Butter plant and a Casein plant producing Acid & Rennet Casein powders. The second is a cheese plant making 25 kg blocks cheddar cheese, and thirdly the Whey plant which houses a Lactose plant, whey protein isolate manufacturing and other whey powders. The site operates 24 h a day all year round albeit



Source: Authors' own work

Figure 1.
Aerial photograph of the Ballyragget processing site, with key plants labelled

with a reduced output during the winter shutdown, there are over 400 employees on site across operations, quality, R&D and admin.

This project is being led by the maintenance department. The maintenance team comprises 26 technicians supported by 4 maintenance managers and 3 maintenance planners, they are responsible for ensuring the plants operate safely and reliably for the season. During the traditional winter shutdown, the team service and maintain the equipment preparing it for the next season, this period is referred to as "The Overhaul" and is a critical component of the sites' performance. An effective overhaul ensures the plant runs well for the year with minimal breakdowns, a bad overhaul could result in significant downtime and loss of processing, having major financial impacts.

2.1 Phases of turnaround maintenance

The key tools and components of the four phases of TAM are depicted (See Supplemental Material SM1). The most important elements are creation of the Scoped Work List during the Initiation phase, this is the foundation of the program. What follows in Preparation is generation of a comprehensive material, quality and resourced work plan and structure, ensuring everything ready to implement prior to the overhaul Execution phase. The actual execution of the work plan is the nuts and bolts of the process and is typically a function of materials, manpower and on the ground management and coordination. Once all physical activity is complete, equipment start-up and testing can be undertaken to ensure all elements have been completed to the required standard. Learnings from the campaign can then be gathered in the Termination phase and built into the following years plan as an improvement and feedback step, akin to Demings PDCA cycle.

2.2 Phases of Define-Measure-Analyse-Improve-Control

The DMAIC toolkit contains many tools that can be applied during the five-step process, the tools selected for this case study are visualised (See Supplemental Material SM2). All elements listed form part of the LSS toolkit (Brassard *et al.*, 2002) and contribute to the formation of a structured approach to tacking a process problem or identifying an area that needs improvement. Application of each element will be expanded further as part of the implementation steps.

2.3 New hybrid define-measure-analyse-improve-control–turnaround maintenance

Combining the relevant elements of TAM and DMAIC will result in the creation of the novel Hybrid DMAIC-TAM set of process steps and associated tools. This methodology is strongly aligned with the DMAIC structure as it is the more widely used methodology; however, the TAM elements are included in the appropriate stage of the model, and it is envisaged that the combination of the two techniques will build on synergies and complement each other when it comes to application in practice. A detailed explanation of each phase of the new methodology and the key inputs and outputs is described in Section 2.4.

2.4 Case study introduction

2.4.1 Define stage. The first step of the methodology, seen by many as the most important is where the direction for the project is set, and the foundation established. In this case study the project team meet, review the requirements for *Define* phase and work through the elements outlined in Figure 4 using the DMAIC/TAM methodology as a roadmap. A charter is created which includes a clear and agreed Scope with involvement of the project team and sponsors from the site leadership team (See Supplemental Material SM3). Delivery of this project is a key element of the company strategy so having visible and engaged senior leaders supporting efforts will be crucial for the team and ensures wider site employees understand the importance and relevance of the activity.

The project team formed and although led by the maintenance department, includes members from production, material stores, milk planning and finance departments – all of whom would be impacted by and involved in project delivery. An exercise will be completed to understand the impacts the project has in terms of Suppliers-Inputs-Process-Outputs-Customers (SIPOC), and this should also aim to incorporate the voice of the customer (VOC) feedback and requirements.

The generation of the overhaul "worklist" is a critical element in this stage as it becomes the framework that all other elements hang from. This involves assessing plant and equipment structures from the three factories and ensuring all the key items are covered on the overhaul list, this list of equipment can be quite substantial but needs to be extensive, so no critical items are overlooked leading to plant failure. This significant element of work should be broken out by functional area and the local team, led by the maintenance manager and planner work through it to develop an area specific list. Each piece of equipment should be assessed on its overhaul requirements in line with original equipment manufacturers (OEM) guidelines and best practice. Once the completed work list is generated, it forms the basis of the next phase.

2.4.2 Measure stage. The *Measure phase* is based on the expansion process of the worklist from the *Define phase.* The worklist was segmented into the different processing areas which were led by several project teams. The processing areas are further used for the preparation of maps which guide the team with the process review by measuring the current team capability against the desired capability that is required for each area and particularly the equipment. Where the capability is not possible to predict accurately, the site teams can require the assistance of OEMs or service representatives.

The processing maps with the accurately estimated capabilities are further integrated into the detailed workplans. These can be cascaded from the worklists and the parts and materials required for each piece of equipment including the Bill of Materials (BOM). The BOMs are mandatory to provide as a part of *Measure phase* to ensure that all materials which were required are on site to enable work completion on time for the further consideration as a part of the quality control plan.

The final step of the *Measure phase* is a review of the quality control plan for each area. As this project was undertaken in a dairy plant, typical items for consideration to include as a part of a quality control plan are greases and lubricants. This can ensure that no contaminants have entered the process stream, and all parts of the dairy plant are cleaned and sanitised before being brought back into service after the maintenance. A quality liaison supervisor ensures the accurate formulation of each quality control plan to follow the food safety regulations. The liaison supervisors have as detailed two-step discussion of the quality control plan with their teams prior the final plan signation and presentation to the company board. The final plan after the board members' approval is stored in the internal company folder and concurrently integrated into the automatic controlling system of the dairy plant to train further the unique AI model that dairy is currently in a process to develop.

2.4.3 Analyse stage. The *Analyse* phase takes the data and outputs from the previous phases and uses them to verify the validity of the assumptions and actions taken to date. The overall schedule of works is assessed and tested for each area to ensure it adequately meets customer and project requirements in terms of timing and technical detail. The materials management kitting process, highlighted as a critical process and given a dedicated central resource, is reviewed and verified to ensure it would be capable of supporting the overhaul activity. Picking and kitting of parts and components for the work orders should be scheduled in advance of shutdown so materials will be ready-to-go on day one of overhaul.

Finally, detailed analysis of the resources required will be undertaken to ensure everything is in place to meet project scope expectations. The financial impact of the overhaul would need to be understood in advance of committing resources, a report outlining the additional financial requirements needed over and above normal to meet the project schedule needs to be approved.

The output from the Analyse phase can be a detailed action plan and schedule that once executed meets the customer requirements delivering an effective plant overhaul.

2.4.4 Improve stage. The *Improve* phase, is the most externally visible and exciting phase, here the physical work takes place. The critical element in this step is that the plan is executed as outlined and that any deviations are highlighted and addressed immediately. Typically, the nature of overhaul work throws up surprises, equipment that you planned to spend 6 h overhauling has unforeseen challenges and takes twice as long to complete, having a knock-on effect to other jobs unless progress is closely monitored.

During this phase, we can validate the quality of our extensive planning and preparation activities, and we assess if the material and parts kitted matched the equipment. We stand over the accuracy of our data from the measure and analyse phases to obtain a clear overview of potential changes for the future.

The physical execution is challenging and labour intensive, the maintenance, OEM and contract support teams require additional support in terms of work permits, health and safety isolations, site inductions and food safety training to ensure there are no barriers to successful overhaul completion. Engineering support and access to equipment manuals will also be key to ensuring all work completed follows manufacturers guidelines and reduces the risk of early equipment failure during start-up.

2.4.5 Control stage. This phase takes place once improvement works are completed and aims to ensure that controls and measures are in place to maintain the performance of the system. The computerised maintenance management system (CMMS) is used to record all activity carried out during the overhaul and in conjunction with the activities of the maintenance planners will be monitored for work accuracy and provide feedback on performance. An overall work completion and validation tracker monitors completion and start-up of each plant area.

A vital part of the feedback loop is managed in this phase, each piece of equipment has a completed maintenance record which highlights potential issues around technician training, or other shortfalls that need to be acted upon before the next overhaul. This feedback and control loop gives early indication of potential issues that may need follow up work or system enhancements. This step allows the technicians to update the equipment and work list with status and condition information about the plant, i.e. nearing end of life, tolerances approaching the OEM limit, asset requires replacement at next overhaul. The control phase looks at future iterations of the overhaul and ensure any errors or oversights made in one overhaul are corrected so they do not reappear in the future, examples would be BOM errors or poor estimation of time required to complete a work activity.

3. Results

3.1 Define-measure-analyse-improve-control–turnaround maintenance hybrid model

The results of the research and case study are outlined in three parts, firstly, a presentation of the DMAIC-TAM model developed; secondly, an overview of the business results achieved in the case study; and finally, an account of the results generated through its application in the plant. Combining DMAIC and TAM resulted in the novel DMAIC/TAM Hybrid model, Figure 2, providing an effective structured approach and suite of execution tools that can be used when completing major maintenance overhaul initiatives in any industry.

The model builds on the proven improvement approach of the DMAIC process and adds the specific and targeted elements of turnaround maintenance, common items were reinforced, like Charter and Scope, while unique TAM elements were integrated seamlessly. Each TAM element found a home within the DMAIC structure and enhanced the effectiveness of the process step, ensuring that the specialised maintenance steps were completed at an appropriate stage of the project and areas for improvement were highlighted and executed.

3.2 Business results achieved in the case study

The application of the DMAIC-TAM model in the case study exceeded the initial project objectives and delivered exceptional results for the business. The improvements delivered a reduction in the duration of the overhaul period by 36% from 11 weeks to 7. These 4 weeks enabled an extension to the processing season, facilitating the processing of an additional 107 million litres of milk on site. Positive market pricing meant that this extra processing was worth €8.9m of additional value to the business.

While the financial and processing results are laudable, additional business process improvements were also delivered. A site kitting process was established which streamlined material delivery and reduced nonvalue added activity. BOMs were created and validated for all key site equipment which greatly improve internal maintenance planning and business processes. Planning activities were optimised with the automation of CMMS-SAP workorder release a particular highlight, saving 80 man hours of labour annually.

Relationships with suppliers and service providers were enhanced, new partners were identified and engaged to support overhaul delivery. Cooperation between production and maintenance departments reached new levels, specifically around utilisation of seasonal production staff to assist with overhaul activity and alignment on shutdown requirements. Ultimately, the project delivered an enhanced maintenance overhaul model and template for the business that could be adapted and improved to deliver further gains in subsequent years.

3.3 Results from each stage of the define-measure-analyse-improve-control–turnaround maintenance hybrid model

3.3.1 Define stage. The results of the define stage were critical in shaping the direction the project followed and contributed to its successful delivery. The Charter and Scope documents were developed and agreed with the project and site leadership teams, shown in Figure 3, they acted as a roadmap for the team and guided them to ensure they stayed

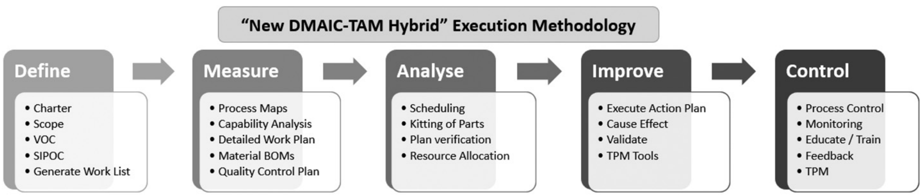


Figure 2. New hybrid DMAIC-TAM methodology – with combined tools and elements

Source: Authors' own work

Enterprise Improvement Project - Charter

Student Name and Student Number	Connor Moore (9420886)	Project Name	**PROJECT FROST** - Use Lean Tools and Techniques to Increase Dairy Processing Season by Reducing the winter Overhaul Period

Problem/Opportunity Statement	Process Time Required
Historically the Dairy industry operates with the natural seasons and processes cows milk after they have calved in the winter - the season runs from mid February to mid November and production facilities run at max capacity during the year. At the end of the season all facilities and equipment undergo intensive maintenance to prepare them for the next season. The opportunity exists to extend the production season further by reducing the time required for the Annual Winter Overhaul. This has the potential to deliver additional value to the business in terms of extra processing capacity	Extensive planning and feasibility study required and interdepartmental cooperation. Project feasibility & Research to start Q2 2022 in preparation for execution (partial or otherwise) in December 2022 / January 2023

Objectives	Assumptions
Reduce the duration of winter overhaul by 30% Process 100 million additional litres of milk	Business support for project team, resources and freedom to succeed Sufficient amounts of Milk available to Process

Scope and Boundaries	Risks
In Scope: Ballyragget Plant Overhaul, 2022 Ballyragget Milk Plan 2022-2025 Ballyragget Site Strategic plan	Availability of specialist Resources Changes to the business environment Lack of Quality Milk for processing Union & Operational risks

Milestones	Dependencies
Complete review of site overhaul plan Apply Lean tools and techniques to existing Maintenance regieme Quantify minimum achieveable window to complete overhaul - Update Milk Plan Plan and execute Lean Overhaul - allowing extended production season	Support from production and Maintenance teams (resources & flexibility) Availability and cooperation of OEMs HR support and cultural acceptance / change management

Justification	Resources
Potential for approx €7million of additional value to the business if Ballyragget extends production window - due to value in its specific product ranges vs other processing sites	Maintenance Planning resource Availability of specialist contractors Capital Expenditure to facilitate investment if required

Source: Authors' own work

Figure 3. Project charter developed during the Define stage to guide the project team

within scope for the duration of the project. It was regularly referred-to when additional requests that may have led to scope creep were proposed, it proved invaluable in protecting the integrity of the agreed scope. The clarity of purpose it reinforced was a key driver in ensuring the project team had a "True North" to keep them on course to deliver on commitments made in the charter.

A VOC exercise was undertaken, the customers impacted by the project were primarily production departments, commercial team, farmers and milk planning, unions, maintenance team and third-party service providers (See Supplemental Material SM4). The items raised in the VOC were considered during scope generation and useful when completing the SIPOC exercise ensuring oversights were minimised (See Supplemental Material SM5). Key items raised during the VOC centred around requirements for quality controls to be maintained during the project, nervousness around the potential supply chain impact on materials deliveries and concerns that the required skilled labour would not be available to meet the requirements of the overhaul program, these concerns were addressed by the project team during the project.

The unique TAM element that enhanced this stage was the generation of the "Work List", which is an overall list of processing lines by plant area that had to be included for consideration in the overhaul. The output of this process was developed by the maintenance manager and team in each plant. It was formulated from exports taken from the established CMMS database. SAP is used in this case study. An example of the work list for the Whey plant (See Supplemental Material SM6), detailing the different processing lines within the plant and a summary of the equipment requiring overhaul. This worklist was a crucial input to the Measure phase.

3.3.2 Measure stage. Delivering outputs from the measure phase was quite an undertaking in terms of engineering workload with extensive reviews of data required to convert the worklist from the define phase into a more detailed work plan structure that could be used to formulate the overall schedule in the analyse phase. The maintenance manager and planner in each area took the worklist and expanded it to individual equipment level, in total over 11,500 pieces of equipment had to be considered. This activity took a number of months to complete as it was carried out in line with team members day jobs, there was only a dedicated resource for overall program management. The maintenance requirements for the equipment had to be considered and defined in a systematic manner in line with OEM guidelines and best practice. Each piece of equipment had its own list of tasks, replacement parts and hours necessary to complete the job assigned. This information was converted to a work order and loaded onto the CMMS system which would be used to track the order to completion.

A capability analysis was completed where the skills needed for each area were quantified and compared to the resources which the site had in its existing maintenance team. The output highlighted a deficiency in the quantity of maintenance hours available to complete the work. Mitigation plans were established to address this shortfall, including complementing the existing team with labour from local companies, resources from other Tirlán sites that were not in overhaul. Seasonalworkers were hired as "helpers" to assist the core teams in job execution.

The BOM for each machine was formed from the maintenance manuals in conjunction with a review of the historical parts used in previous overhauls. A master BOM for the site was issued to the stores department to ensure they had adequate time to arrange for the parts to be ordered and delivered before the shutdown. Delays waiting on parts would adversely affect the ability to meet the tight schedule (See Supplemental Material SM7). Following this exercise, 1170 different components were identified as being required in various quantities to facilitate the planned work. The stores were charged with managing the supply chain to ensure these parts were in stock before the overhaul commenced.

In conjunction with the quality department, rules and procedures were communicated to all outlining the hygiene and reporting requirements during the overhaul. Each plant maintained its production status gowning and hygiene processes, minimising the opportunity for pathogen entry to the plants and reducing the time required for pre-production start-up cleaning, allowing additional wrench time for the maintenance teams. All teams were briefed on this Quality Control Plan. The process for reporting defects was identified to ensure food safety by protecting the product streams from contaminants which could appear in a system through the pumps damages or missing rubber seals on the valves. All seals removed from valves were bagged, condition recorded and passed to the quality team for review to ensure product integrity was maintained. The quality department also completed environmental sampling and audits to ensure compliance.

3.3.3 Analyse stage. The key outputs from the analyse phase was generation of the plant specific work schedule for each area. This was created in collaboration with the milk planning team to ensure the schedule agreed with the overall processing requirements of the business. This documented plan outlined, which equipment would be completed weekly in each plant, included estimates of the electrical and mechanical labour required to complete work, and in total, 9,808 manhours were required to complete overhaul works on site.

Table 1 shows that estimated man hours exceeded available hours by 2,397 so efforts were needed to close this gap. Otherwise, the project goals would not be met. Initiatives were identified and implemented to address this shortfall. A review of the worklist was undertaken and items that were non-specialist, seen as non-critical to quality or safety, were completed by external service providers. Typically, these were high volume repetitive tasks like valve servicing that involved the removal of process valves from the lines, replacement of rubber seals and reinstallation of 892 valves.

OEMs were used to work on their own equipment, freeing up the site teams to work on higher level equipment. The overhaul of the centrifugal separation equipment is an example of OEMs' use due to their large size requiring a labour intensive and extensive disassembly to access serviceable components. All work was planned through the DMAIC/TAM process with individual schedule of works provided by each vendor ensuring they would be able to meet the time requirements (See Supplemental Material SM8). Other equipment like vacuum pumps and blowers were overhauled by third party providers under the supervision of site teams, thus ensuring the team retained ownership and responsibility for the maintenance of the equipment and could stand over the quality of the work completed, ensuring correct procedures, lubricants and components were used (See Supplemental Material SM9).

During the development of the DMAIC/TAM model, materials planning and technician tool time emerged as crucial elements of the TAM approach. One of the most valuable components of maintenance work is the technician's time, companies record "Wrench Time" as a measure of the effective utilisation of the technician's time. Highlighted in the TAM model and supported by local studies it was evident that a large amount of time in the overhaul was lost travelling to the stores to collect parts. The case study site is one of the largest in Europe and although the store is located centrally, substantial time is wasted walking to and from the stores. An analysis of the routes and travel times from the workshops was conducted and spaghetti diagram generated to quantify the existing process in Figure 4, it was clear that a substantial amount of time, 551 min daily was wasted (Table 2).

To address this, a "kitting" process was established where the kit of parts is assembled in the engineering stores for each planned job (see red tote box) and is delivered to the maintenance workshops by the stores team on a delivery route in advance of the scheduled work for the day, (See Supplemental Material SM10). This enabled the technician to select a box from the workshop and it contained all the parts needed for the job, there was no time wasted travelling to stores and no parts shortages, as the tote would not be released for a job

Labour requirement	Electrical hours		Mechanical hours	
Plant	Required	Available	Required	Available
Cheese	506	490	1,474	1,252
Dairy	320	300	583	514
Plant 1	600	749	1,375	890
Whey	1,139	840	2,090	876
Butter	270	200	830	720
Services	300	370	321	210
Totals	3,135	2,949	6,673	4,462
Shortfall		−186		−2,211

Source: Authors' own work

Table 1. Man-hour requirements for overhaul execution

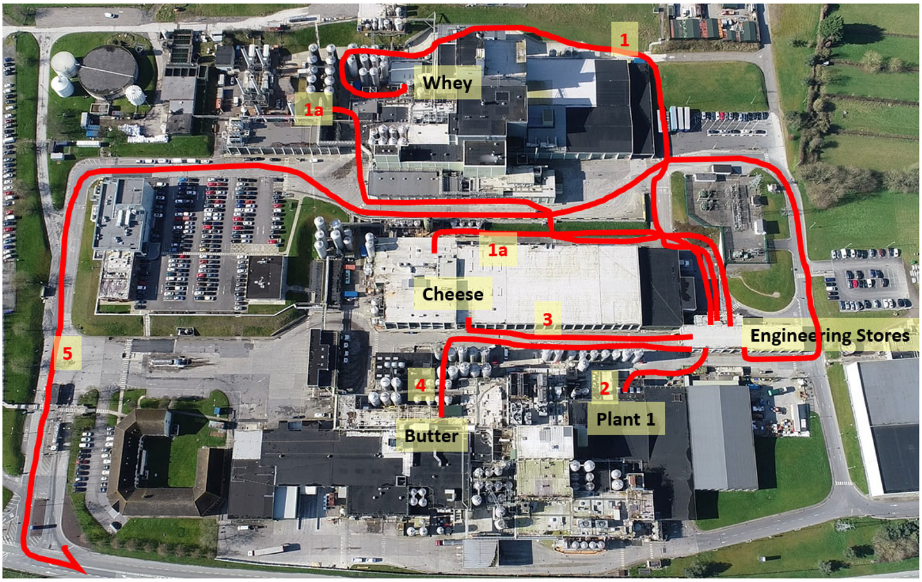


Figure 4.
Spaghetti diagram of routes to stores from each of the workshops

Source: Authors' own work

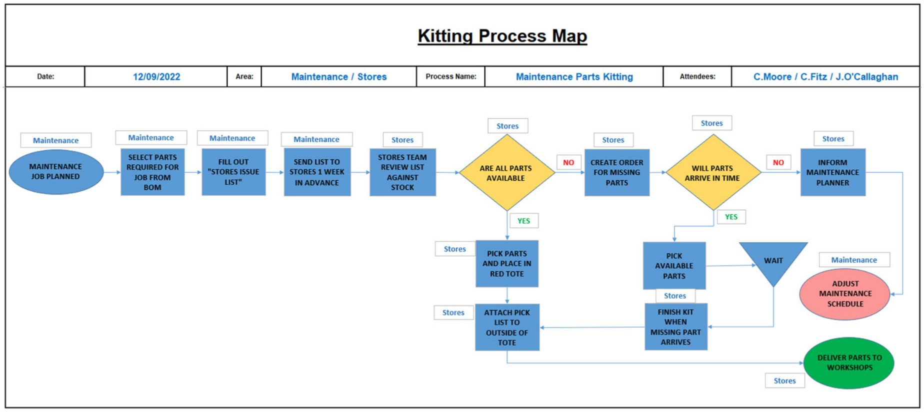
Table 2.
Route detail and times taken for maintenance technician to walk to stores for parts (Figure 4)

Area	Route	Distance, m	Time, m	People no. pro journey	Time, min
Whey	1	480	5.8	48	288
	1a	500	6.0	48	288
Plant 1	2	80	1.0	30	30
Cheese	3	130	1.6	24	41
	3a	150	1.8	24	41
Butter	4	200	2.4	30	72
Services	5, *Van	1200	5.0	24	120
Daily time wasted walking (excluding wait times in stores)					*551*

Source: Authors' own work

unless complete. Each tote contained a parts list and CMMS job number that the technician ticked off as he used the parts, any unused or incorrect items were highlighted, and the system updated when the tote was returned to stores. A process map of the kitting operation is shown in Figure 5 and a sample output from this activity/a kitting list call off sheet (See Supplemental Material SM11). The combination of these initiatives released additional wrench hours for the maintenance teams, allowing them to focus on higher value work and assisted in making up the shortfall in available hours ensuring the project objectives were achieved.

3.3.4 Improve stage. This is the most time sensitive phase of the overhaul and each area managed execution and workload closely on a day-to-day basis during the overhaul period.



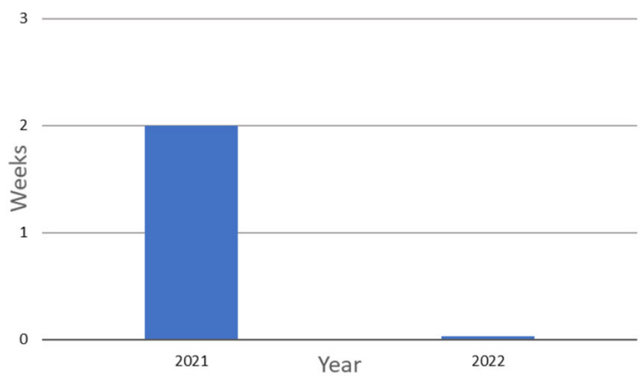
Source: Authors' own work

Figure 5. Process map developed for the maintenance parts Kitting operation

The action plan was printed and posted in each maintenance workshop and used as a live tracker to monitor progress, as the technicians complete work they mark it off on the plan so it is clearly visible to others which jobs are still outstanding. They also updated the jobs electronically on the CMMS, including confirming the time for each job, this actual time could then be compared to the planned time to aid with scheduling of resources for similar jobs and used as a guide for future planning activities.

Contractors and OEMs are also on site during this phase completing maintenance and service works on their equipment. Their work requires more supervision as they are not as familiar with site rules and procedures as existing maintenance teams. All contractors received specific health and safety induction and their work was closely controlled with work permits to ensure they were operating safely. Feedback from their work was also logged on CMMS to maintain equipment history and service records.

Figure 6 shows that the total processing time reduced from 2 weeks in 2021 to 1 h and 19 min in 2022. The state-of-the-art has emphasised the maintenance planners as a key resource during the overhaul. This is because they are responsible for ensuring the CMMS



Source: Authors' own work

Figure 6. Almost two weeks work saved through Kaizen of releasing work orders in SAP

system is updated and all jobs executed correctly. A major work item for them is activating the workorders on the CMMS. Due to the amount of work orders that are required the planners spend a total of two weeks clicking through and releasing orders, this is non-value added at this critical time. This was targeted in a mini-Kaizen to improve the process. As a result of the Kaizen activity the process was automated through the application of macros and some simple coding, reducing the number of mouse clicks from 20,000 to 2. The automatisation and better process control at the dairy plant instead of the manual operations' planning led maintenance management to focus on more important tasks in the overhaul (See Supplemental Material SM12). The newly developed automatisation system allowed to replace the manual work of the daily routine tasks in the plant overhaul.

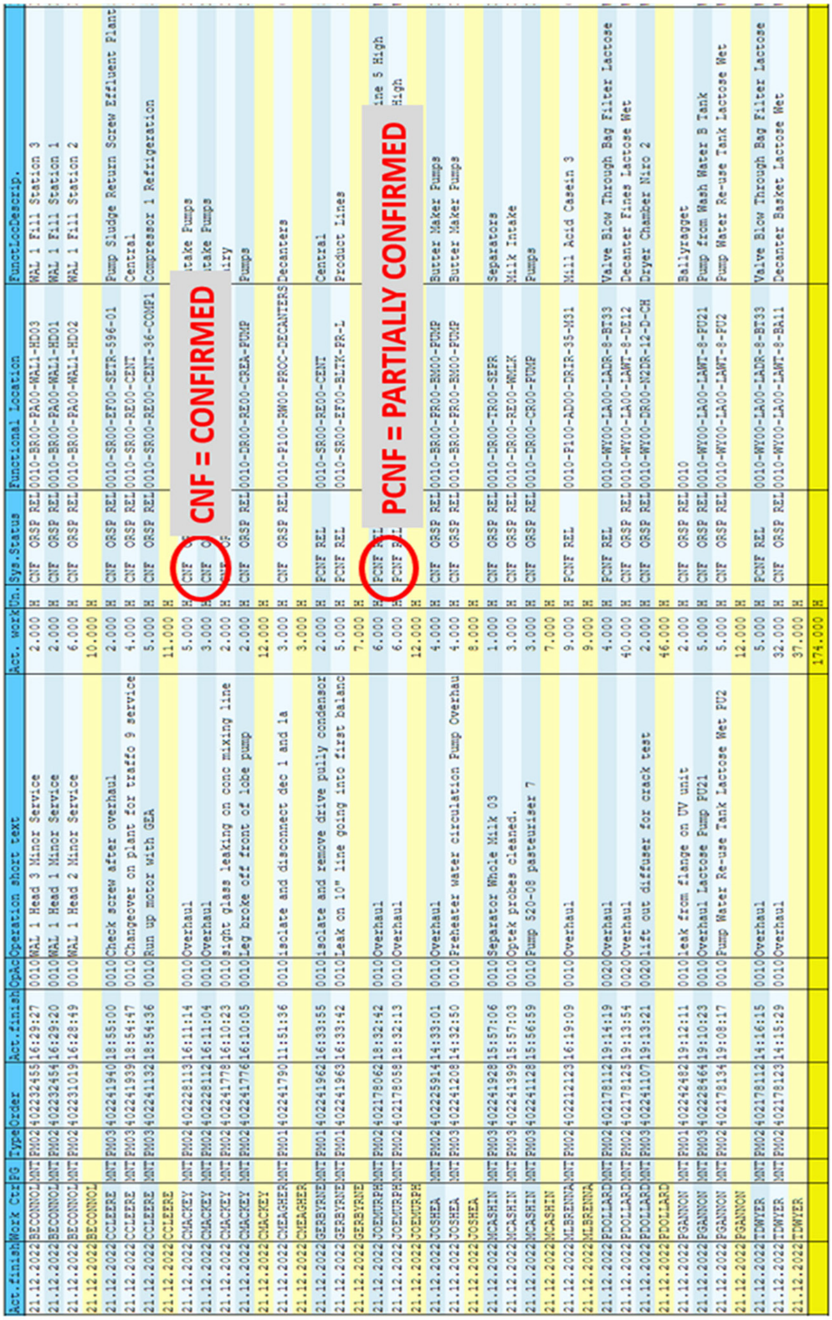
During the improvement and execution phase monitoring and communicating progress is a key requirement for the team. Daily updates were issued during morning GEMBA meetings on the production floor, the maintenance and production teams would meet to review progress from the previous day, plan for the day ahead and any potential roadblocks or additional support required would be raised. Reports from the CMMS on work completed were automatically emailed from the system daily showing which jobs were completed by each technician; if jobs were only partially completed, it allowed planners to intervene and assess if support was needed. Figure 7 shows an example of this CMMS report. It details each technicians' work orders, time spent on the job and its current status, whereas CNF means the job is finished and PCNF indicates a partially complete job that requires follow-up. As the overhaul progressed a weekly report was issued to stakeholders updating the status in each area, this was an important communication tool keeping all informed. The update also let the production planning and commercial teams know that the overhaul was on-track to meet schedule so that external milk planning and supply to sites could be managed. The format was the same for each area, a sample is shown in Figure 8; it displays overall status for the plant in a donut-chart, showing percentage of jobs complete, in progress or outstanding.

Figure 8 illustrates a status in each sub area of the plant was also displayed and finally commentary included to let stakeholders know detail of current activity and next steps.

3.3.5 Control stage. The purpose of the control phase was to ensure processes were in place to enhance the maintenance systems for the coming year in terms of reliability and pre-planning the following years overhaul. The work report of each job was reviewed to ensure it was completed accurately. Any items requiring follow on work or flagged as approaching end of life were collated and added to the sites capital expenditure plans for asset replacement during the next years overhaul. The feedback sheets from the kitting process were collated and used to update BOMs and correct any kitting errors. This feedback is invaluable in maintaining accurate BOMs not only for overhauls but also for ongoing maintenance during the year, ensuring parts are in stock to deal with breakdowns.

When the overhaul was complete the maintenance team in each area met and reviewed existing maintenance, this is a valuable exercise as it takes on board the physical condition of the equipment in the area, looks at the existing maintenance structure and intervals and makes an assessment as to whether it is fit for purpose or not. An example would be the butter team, who after overhauling the butter churn motor and gearbox on its five-year cycle noticed the bearings and seals were a little dry and the wear was slightly greater than expected, the decision was made to reduce the frequency on this job to four years, this should reduce the risk of unplanned failure and downtime.

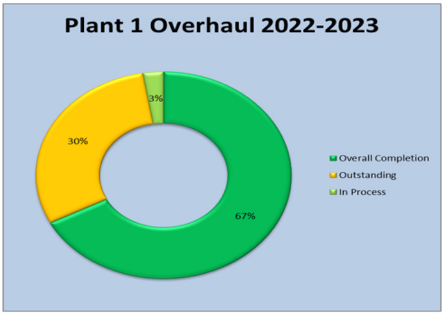
The opposite occurred on the Dairy CIP pumps. They were traditionally on an annual bearing and seal change which has been extended to a two-year-cycle following an assessment on the condition of the equipment during the overhaul. This was supported by



Act.finish	Work Ctr	PG	Type	Order	Act.finish	OpAc	Operation short text	Act. work	Un.	Sys.Status	Functional Location	FunctLocDescrip.
21.12.2022	BECONNOL	MNT	PM02	402232455	16:29:27	0010	WAL 1 Head 3 Minor Service	2.000	H	CNF ORSP REL	0010-BR00-PA00-WAL1-HD03	WAL 1 Fill Station 3
21.12.2022	BECONNOL	MNT	PM02	402232454	16:29:20	0010	WAL 1 Head 1 Minor Service	2.000	H	CNF ORSP REL	0010-BR00-PA00-WAL1-HD01	WAL 1 Fill Station 1
21.12.2022	BECONNOL	MNT	PM02	402231019	16:28:49	0010	WAL 1 Head 2 Minor Service	6.000	H	CNF ORSP REL	0010-BR00-PA00-WAL1-HD02	WAL 1 Fill Station 2
21.12.2022	BECONNOL							10.000	H			
21.12.2022	CCLEERE	MNT	PM03	402241940	18:55:00	0010	Check screw after overhaul	2.000	H	CNF ORSP REL	0010-SR00-EF00-SETR-596-01	Pump Sludge Return Screw Effluent Plant
21.12.2022	CCLEERE	MNT	PM03	402241939	18:54:47	0010	Changeover on plant for traffo 9 service	4.000	H	CNF ORSP REL	0010-SR00-RE00-CENT	Central
21.12.2022	CCLEERE	MNT	PM03	402241132	18:54:36	0010	Run up motor with GEA	5.000	H	CNF ORSP REL	0010-SR00-RE00-CENT-36-COMP1	Compressor 1 Refrigeration
21.12.2022	CCLEERE							11.000	H			
21.12.2022	CMACKEY	MNT	PM02	402228113	16:11:14	0010	Overhaul	5.000	H	CNF [illegible]	[illegible]	take Pumps
21.12.2022	CMACKEY	MNT	PM02	402228112	16:11:04	0010	Overhaul	3.000	H	CNF [illegible]	[illegible]	take Pumps
21.12.2022	CMACKEY	MNT	PM02	402241778	16:10:23	0010	sight glass leaking on conc mixing line	2.000	H	[illegible]	[illegible]	iry
21.12.2022	CMACKEY	MNT	PM02	402241776	16:10:05	0010	Leg broke off front of lobe pump	2.000	H	CNF ORSP REL	0010-DR00-RE00-CREA-PUMP	Pumps
21.12.2022	CMACKEY							12.000	H			
21.12.2022	CMEAGHER	MNT	PM01	402241790	11:51:36	0010	isolate and disconnect dec 1 and 1a	3.000	H	CNF ORSP REL	0010-P100-RW00-PROC-DECANTERS	Decanters
21.12.2022	CMEAGHER							3.000	H			
21.12.2022	GERBYRNE	MNT	PM01	402241962	16:33:55	0010	isolate and remove drive pully condensor	2.000	H	PCNF REL	0010-SR00-RE00-CENT	Central
21.12.2022	GERBYRNE	MNT	PM01	402241963	16:33:42	0010	Leak on 10" line going into first balanc	5.000	H	PCNF REL	0010-SR00-EF00-BLTK-PR-L	Product Lines
21.12.2022	GERBYRNE							7.000	H			
21.12.2022	JOEMURPH	MNT	PM02	402178062	18:32:42	0010	Overhaul	6.000	H	PCNF [illegible]	[illegible]	ine 5 High
21.12.2022	JOEMURPH	MNT	PM02	402178058	18:32:13	0010	Overhaul	6.000	H	PCNF [illegible]	[illegible]	High
21.12.2022	JOEMURPH							12.000	H			
21.12.2022	JOSHEA	MNT	PM02	402225914	14:33:01	0010	Overhaul	4.000	H	CNF ORSP REL	0010-BR00-PR00-BM00-PUMP	Butter Maker Pumps
21.12.2022	JOSHEA	MNT	PM03	402241208	14:32:50	0010	Preheater water circulation Pump Overhau	4.000	H	CNF ORSP REL	0010-BR00-PR00-BM00-PUMP	Butter Maker Pumps
21.12.2022	JOSHEA							8.000	H			
21.12.2022	MCASHIN	MNT	PM03	402241928	15:57:06	0010	Separator Whole Milk 03	1.000	H	CNF ORSP REL	0010-DR00-TR00-SEPR	Separators
21.12.2022	MCASHIN	MNT	PM03	402241399	15:57:03	0010	Optek probes cleaned.	3.000	H	CNF ORSP REL	0010-DR00-RE00-WMLK	Milk Intake
21.12.2022	MCASHIN	MNT	PM03	402241128	15:56:59	0010	Pump 520-08 pasteuriser 7	3.000	H	CNF ORSP REL	0010-DR00-CR00-PUMP	Pumps
21.12.2022	MCASHIN							7.000	H			
21.12.2022	MLBRENNA	MNT	PM02	402212123	16:19:09	0010	Overhaul	9.000	H	PCNF REL	0010-P100-AD00-DRIR-35-M31	Mill Acid Casein 3
21.12.2022	MLBRENNA							9.000	H			
21.12.2022	PDOLLARD	MNT	PM02	402178112	19:14:19	0020	Overhaul	4.000	H	PCNF REL	0010-WY00-LA00-LADR-8-BT33	Valve Blow Through Bag Filter Lactose
21.12.2022	PDOLLARD	MNT	PM02	402178125	19:13:54	0020	Overhaul	40.000	H	CNF ORSP REL	0010-WY00-LA00-LAWT-8-DE12	Decanter Fines Lactose Wet
21.12.2022	PDOLLARD	MNT	PM03	402241107	19:13:21	0020	lift out diffuser for crack test	2.000	H	CNF ORSP REL	0010-WY00-DR00-N2DR-12-D-CH	Dryer Chamber Niro 2
21.12.2022	PDOLLARD							46.000	H			
21.12.2022	PGANNON	MNT	PM01	402242482	19:12:11	0010	leak from flange on UV unit	2.000	H	CNF ORSP REL	0010	Ballyragget
21.12.2022	PGANNON	MNT	PM03	402228464	19:10:23	0010	Overhaul Lactose Pump PU21	5.000	H	CNF ORSP REL	0010-WY00-LA00-LAWT-8-PU21	Pump from Wash Water B Tank
21.12.2022	PGANNON	MNT	PM02	402178134	19:08:17	0010	Pump Water Re-use Tank Lactose Wet PU2	5.000	H	CNF ORSP REL	0010-WY00-LA00-LAWT-8-PU2	Pump Water Re-use Tank Lactose Wet
21.12.2022	PGANNON							12.000	H			
21.12.2022	TDWYER	MNT	PM02	402178112	14:16:15	0010	Overhaul	5.000	H	PCNF REL	0010-WY00-LA00-LADR-8-BT33	Valve Blow Through Bag Filter Lactose
21.12.2022	TDWYER	MNT	PM02	402178123	14:15:29	0010	Overhaul	32.000	H	CNF ORSP REL	0010-WY00-LA00-LAWT-8-BA11	Decanter Basket Lactose Wet
21.12.2022	TDWYER							37.000	H			
								174.000	H			

Source: Authors' own work

Figure 7.
Work status report issued daily from CMMS used by planners to update execution status



Plant 1 Tracker 2022/2023	
Area	**Completion**
25kg & Bag Off	85%
Acid Casein	59%
Rennet Casein	60%
Recon	100%
MPC	73%
Niro 1	70%
Wiegand & RO	75%
CIP	56%
Overall Completion	**67%**
Outstanding	**30.0%**
In Process	**3%**

Tirlán

WEEK 5 / 25 Jan 2023

Bag off
- Works essentially complete, running line this week
- Some project works ongoing in Bulk pallet system

Acid Casein
- Revisiting acid casein next week once rennet finalised

Rennet Casein
- Pillet drier now complete
- GEA finalizing decanters (some repairs due on Dec 1 hood)
- Sifters being reassembled this week on dry side

Recon
- Complete

MPC
- Mostly Complete – running this week

Niro 1
- Overhaul/Inspection of Atomisers outstanding

Weigand
- Run and check of 2 pumps outstanding

CIP
- Run and check of 3 pumps outstanding

Figure 8.
Weekly overhaul status report issued to site management team during overhaul execution

Source: Authors' own work

an excerpt from SAP (See Supplemental Material SM13). The planners can now look at these cases and adjust the annual overhaul plan accordingly, potentially rebalancing workload between years and streamlining an areas overhaul.

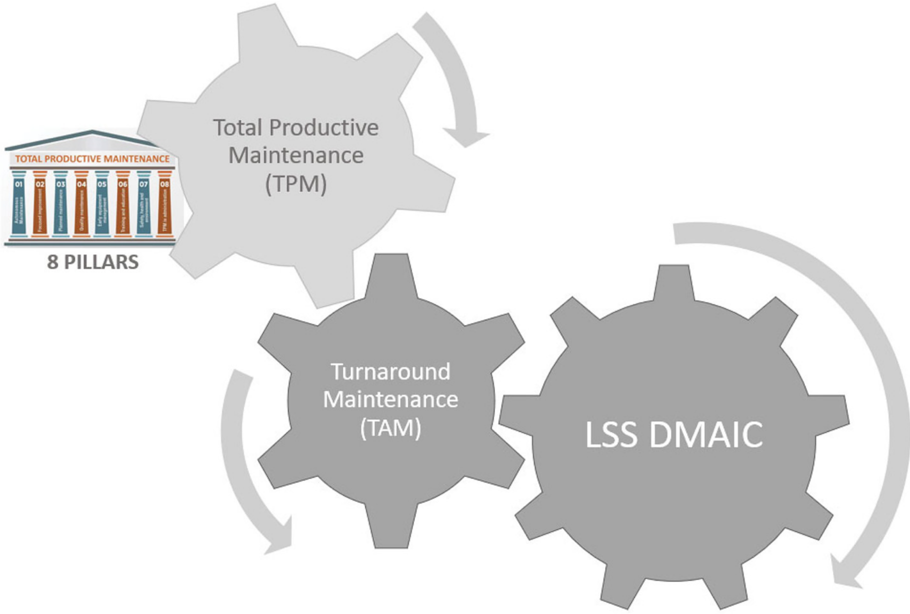
4. Discussion

This research and case study has demonstrated that combining the DMAIC process with the elements of TAM created a novel DMAIC-TAM hybrid methodology that can be applied effectively in the dairy industry. The largest Irish dairy has not used any digital strategy for the quality control and process improvement during maintenance overhaul periods prior this DMAIC-TAM methodology was integrated. The overall project goal was to reduce the duration of the plant's annual maintenance overhaul. DMAIC is widely used across discrete manufacturing industries due to its structured approach to problem solving (de Mast and Lokkerbol, 2012). It has also found widespread use in the dairy industry, and there are many good examples of its application in problem solving and improvement initiatives in Irish dairy (Trubetskaya *et al.*, 2023). Turnaround maintenance is a mainstay in the oil and gas and processing industries (Pokharel and Jiao, 2008) and (Duffuaa *et al.*, 2004), but very little has been written on its application in a dairy sector. So, this research uniquely combines both approaches into a hybrid model. The combination of both approaches was required to identify improvement opportunities with DMAIC and execute the physical overhaul with TAM.

The business results of the case study highlighted the financial benefits to the processor of extending the production season, namely, €8.9m in additional value. There is also benefit to the farmer in extending the season in terms of increased price for his low season milk (Ramsbottom *et al.*, 2020) and better utilisation of his farm assets (Läpple *et al.*, 2012). In addressing the challenges presented in this project and looking to the years ahead it would be worth continuing research in the area of year-round processing of milk in the Irish dairy sector (Geary *et al.*, 2012). Studies have looked at the effect of split calving on Irish dairy farm profitability (Geary *et al.*, 2014). However, this study was completed before the abolition of quotas. The environment has changed significantly since then, and this would be worth revisiting. Ultimately, there is no point in the processing industry moving to a year-round model if the farmers are not on board (Cele *et al.*, 2022).

The DMAIC-TAM model proved to be very successful in the case study delivering a 36% reduction in the duration of the overhaul. However, further enhancements could be made by exploring the suitability of integrating total productive maintenance (TPM) tools into the model. TPM a lean tool, is based on eight pillars that are designed to maximise production/maintenance effectiveness and efficiency (Adesta *et al*, 2018). There are opportunities to improve the model through implementation of autonomous maintenance, where the equipment operators in the plant become the first-line maintainers throughout the year. They carry out greasing and basic condition checks normally completed by MAMF technicians, freeing up resources to work on higher value items and improvement initiatives. Figure 9 illustrates a graphic of the DMAIC, TAM and TPM models and how they could be visualised to complement each other. These are important to consider in the further DMAIC-TAM methodology enhancements as three distinct tools working towards a common goal.

While widely used in chemical industries (Duffuaa *et al.*, 2013), the author believes TAM on its own is not enough in modern processing plants. As a methodology it will assist you in execution of your maintenance activity, but it does little in the way of eliminating non-value-added work or identifying opportunities for improvement. The newly developed DMAIC/



Source: Authors' own work

Figure 9. Visualisation of DMAIC, TAM and TPM (8 Pillars) methodologies complementing each other

TAM methodology that builds on the acceptance of the DMAIC process in industry and coupling with TAMs execution, can easily be integrated into an environment that has already embraced the DMAIC process. In this case study, there were no significant training requirements or change management initiatives required for most of the workforce as the continuous improvement systems and mindset were already established in the enterprise. This was a significant benefit when it came to project execution. DMAIC was like a trojan horse allowing TAM to seamlessly integrate into existing business operations. However, if you were trying to apply DMAIC-TAM in a business that is completely new to LSS, there would be a significant amount of training and change management effort required.

The importance of making the overhaul activity a sitewide program and involving all departments proved very beneficial to the execution and delivery of project goals. Considering non-maintenance or engineering teams through completion of VOC and SIPOC activities lead to wider buy-in and support by other functions. Keeping all stakeholders informed on plans and progress kept support avenues open and communication lines clear. This made what was traditionally seen as a maintenance overhaul into a site-strategic initiative, aligned with the company's long-term strategies.

The value of a properly resourced maintenance planning function cannot be understated. Maintenance planners are central to all activity during overhaul execution. They ensure that the BOMs and kitting arrangements are accurate. They quantify the resources required for each overhaul job and ensure the CMMS is primed and capable of carrying out the necessary transaction to support the overhaul campaign. Post overhaul, it is the planners that take the learnings and feedback from the recorded work history to update the system for the following year. In this project a number of skilled and experienced planners were integrated. They worked in a partnership to deliver a consistent approach across the site supporting the wider maintenance team. Their contribution to generation of plant worklists, BOMs and the kitting process were key to the project's success and goal achievement.

Much of the effort and activity in completing the case study was undertaken "offline" in excel and other standalone software applications. Once data was collated and organised, it was then "loaded" into the CMMS. The system then processed the work orders, booked out parts, recorded job history and resources required for the work completion. This amounted to an element of double jobbing and is one area of improvement that should be explored in follow on overhauls. The CMMS should be used for all planning, scheduling and execution of work. The reason this did not happen is a combination of system restrictions and user skill deficiencies across the business, as it appears to be a limitation in the project team acknowledge.

The establishment of the kitting process, preparing and pre-picking the parts required for a job, was a key contributor to the successful execution of the project. It resulted in maximum tool time for the technicians by eliminating wasted time and materials. It allowed them to remain in the workshop and work on the equipment that they had the correct materials for. The delivery of totes containing replacement parts to point of use was a new invaluable initiative. The next stage in the kitting operation is to generate the list of parts on the SAP system for stores to pick. This would eliminate the manual process piloted during the case study. This may well need system enhancements to facilitate its delivery.

The shorter shutdown window together with manpower capability and resource constraints emphases the importance of trying to spread the overhaul over a wider portion of the year. The results of the capability analysis demonstrated the shortage of maintenance technicians, particularly MAMF qualified. This presented a significant challenge to the project team. Investment in skills and apprentices to become more self-sufficient and reduce reliance on external providers needs to be considered for the future unless the overhaul patterns can be altered. Typically, third party resources are more expensive than in-house technicians. This skills' shortage is not an isolated problem. Currently, there are only 210 fitters forecasted to start the MAMF qualifications with the Irish national training agency which points to a continued shortage in industry generally (www.solas.ie, 2023).

As technology advances, the power of data and the ability to harness, interpret and manipulate it. The "internet of things" and Industry 4.0 are presenting new opportunities to improve industrial performance. The challenge will be to find ways of using technology to monitor machine performance, predict failure, make a diagnosis and schedule pre-emptive maintenance (Kumar and Galar, 2018). Introduction of a condition-based maintenance programs on critical assets is possible. Much of this is possible and available in industry. Sensors, real time data and algorithms become more advanced leading to exciting possibilities and opportunities of Industry 4.0 platform that has a strong potential to revolutionise traditional maintenance practices. Thus, the largest Irish dairy plans to integrate the established DMAIC-TAM model as a part of the unique company AI network in the future projects.

5. Conclusions

The novelty of this work relies on the development of the DMAIC-TAM methodology to optimise maintenance shutdown performance in industry (*RQ1*). The methodology proved its effectiveness and applicability by delivering significant business results, financial benefits, and process improvements on an Irish dairy processing site (*RQ2*). It also provides a roadmap and structure to ensure that the gains and execution methodology established are repeatable and adaptable for future overhauls. This hybrid model has universal applicability in industries where large maintenance shutdowns are fundamental to the sector. Limitations of this study are in the application only on a single site that has already actively engaged in a journey of continuous improvement, and thus, faced no resistance or change management challenges. The success of its application may not be as straightforward if the target site was immature from a lean standpoint. A counterargument to this is that the methodology could be used as a first foray into the lean continuous improvement space for a business, once combined with extensive training and change management programs. Trends in Irish dairy processing post quota are moving the industry towards a year-round production model and thus, having wider impact on the sector as a whole leading to more exciting research opportunities.

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