3D-RDM

3D printing-enabled re-distributed manufacturing

3D Printing Production Planning:

Reactive manufacturing execution driving redistributed manufacturing

Project Report

The University of Nottingham

UNITED KINGDOM · CHINA · MALAYSIA

3DPRG

ASAP research group

As an emerging manufacturing technology, 3D Printing, also known as Additive Manufacturing, is showing significant potential for innovation across a wide range of industrial sectors. Among the advantages of the technology are an ability to generate complex functional geometries and the technology's efficiency in the manufacture of small numbers of products.

This project has explored the feasibility of releasing significant additional value by adopting an optimisation-based manufacturing execution methodology that complements the strengths of 3D Printing. The approach aims at replacing the existing machine allocation process with an integrated production planning tool driven by combined build volume packing and scheduling logic. The demonstrator system created in this project thus helps identify the best possible 3D Printing system for each job in an automated process, including re-distributed settings.

Polymeric multi-material test geometry built using material jetting.

Executive summary

by Dr Martin Baumers, Dr Ender Özcan and Dr Jason Atkin

3D Printing (3DP) technology, also known as Additive Manufacturing, is associated with significant potential for supply chain innovation by enabling manufacturing configurations delivering additional value through differentiated products, for example in terms of production location. It has been suggested that pursuing distributed 3DP supply chains may be the result of strategic deliberation, yet it is also frequently noted that 3DP is prone to higher unit costs than conventional manufacturing. In this report we summarise the findings of a project which establishes an understanding of the relationship between the commercial performance of 3DP and the characteristics of its operation through the development of a demonstrator system.[1]

In most industries 3DP faces the additional challenge of integrating with conventional manufacturing technologies and processes, which are normally operated in a centralised location. Economies of scale form one of the reasons for the dominance of centralised manufacturing, allowing the amortization of substantial costs over large volumes of products for the global marketplace. Complementing such centralised manufacturing, increasingly complex supply chains have emerged. Moreover, the implementation of appropriate supply chains is now seen as a core capability for manufacturing businesses.

In this context, a closer inspection of the typical work flow of 3DP reveals a puzzle: the current process for allocating build requirements to individual (potentially re-distributed) 3DP systems relies on an array of decisions on the operator/technician level, some of which can be automated and all of which will affect the overall efficiency of the 3DP process and the business case for its application. Thus, this project focusses on designing a demonstrator to provide a solution to this puzzle and further our understanding of the implementation of 3DP supply chains. Labelled the "3D Packing Research Application Tool" (3DPackRAT), the software demonstrator shows an avenue to the release of significant additional value by enabling a truly flexible and reactive manufacturing execution methodology that complements the strengths of 3DP. As an integrated approach to the build volume packing and scheduling problems encountered, this tool aims to determine the most appropriate 3DP system for each individual order in an automated process.

Effectively, such tools may allow adopters to leapfrog the gradual evolution of supply chain practise in response to the emergence of 3DP. To achieve this, the integrated computational framework we have implemented enables the inclusion of a wide range of general and location-related aspects in a single optimisation-based production planning procedure. Being fed an order stream, 3DPackRAT is designed to determine the best 3DP system for each build request. Crucially, this approach is also capable of considering the benefits resulting from re-distributed 3DP, driving supply chain structures towards such configurations where beneficial.

Our project was carried out as a collaborative and interdisciplinary programme of work between the 3D Printing Research Group (3DPRG) at the Faculty of Engineering and the Automated Scheduling, Optimisation and Planning (ASAP) Research Group at the School of Computer Science, both at the University of Nottingham, over the course of 2016. The programme consisted of three elements:

- formulation of a portfolio of algorithms, heuristics and operational policies capable of addressing the combined build volume packing and scheduling problem for the baseline 3DP technology (Laser Sintering),
- development and implementation of the demonstrator system 3DPackRAT up to the status of a minimum viable product, allowing experimentation by 3rd parties,
- validation of the demonstrator system by interaction with a group of four industrial domain experts through presentations and live demonstrations, among them high-calibre international members of industry.

The project has demonstrated the possibility of implementing a joined-up approach to build volume packing and machine scheduling in 3DP and has shown that the problem in reality needs to be addressed in a multi-machine and multi-time period setting. Moreover, we have extended existing computational build volume packing methodologies to incorporate temporal aspects to address this problem.

Our interactions with various industrial partners advising the project indicate the requirement for such functionality. The demonstrator described in this report thus provides a first step in addressing the emerging workflow optimisation problem in 3DP in an integrated way.

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[1] This report summarises the outcomes of the project "3D Printing Production Planning: Reactive manufacturing execution driving redistributed manufacturing", which was funded through the 3DP-RDM network. We express our gratitude to the Bit-by-Bit project team at the University of Cambridge and the 3DP-RDM network for their funding and support. Moreover, we acknowledge the outstanding contributions of the doctoral researchers contributing to this project, Warren Jackson and Wenwen Li, both from the School of Computer Science at the University of Nottingham. Additionally, we cordially thank the two industrial members advising our project group, Susan Reiblein and David Knight, for their valuable support and excellent advice throughout this feasibility study. Please visit the project website www.3dpackrat.com for more information.

Problem description

The descriptor 3D Printing (3DP) encompasses a diverse range of material deposition principles, ranging from the selective thermal fusion of particles held in a powder bed to the exposure to UV radiation of photoreactive monomer resins contained in a vat. However, the adoption of 3DP also entails significant variety in possible supply chain configurations. Particularly for the realisation of viable re-distributed manufacturing, the methodology used to configure the supply chain is essential.

Leading to the formulation of this project, an initial investigation into AM supply chains revealed that, despite being subject to the pressure of cost minimisation, the current practise of allocating build requirements to individual (potentially re-distributed) 3DP systems relies on a sequence of decisions at the manager and operator level, some of which can be automated using isolated optimisation tools:

- production planning by determining the machine build schedule,
- machine setup by virtually filling the available machine capacity with product geometry.

However, the structure of this allocation process determines the efficiency outcome of manufacturing execution in the 3DP process. As shown in the available literature on manufacturing control systems, disjointed decision making, even if it includes optimisation processes, is not normally indicative of efficiency.

The project team (from left to right): Dr Ender Özcan, Wenwen Li, Dr Martin Baumers, Dr Jason Atkin and Warren Jackson.

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Contrary to the existing narrative, the process flow in 3DP in reality relies on a number of activities relating to design, production engineering, file handling, post processing and additional downstream considerations. To provide context for the wider problem of handling information in this process flow, this project has shown that it is helpful to formulate a more general framework by combining digital manufacturing processes with the generic work flow of 3DP and downstream life cycle considerations, as shown in Figure 1.

This perspective, formed over the course of this project, stresses that in industrial implementations of 3DP, virtual models of products and processes are built up and passed on throughout individual stages in the overall process. The extant literature on the implementation of digital manufacturing suggests that the ability to successfully deploy such an information system forms a prime source of competitive advantage for manufacturing of the future.

This project and the demonstrator system developed aim to inform efficient 3DP supply chain configuration by addressing two specific elements within this process structure in a joined-up way. By integrating production planning and machine setup activities in a single optimisation-based framework, the performance of 3DP manufacturing execution can be maximised and appropriate supply chain configurations can be determined.

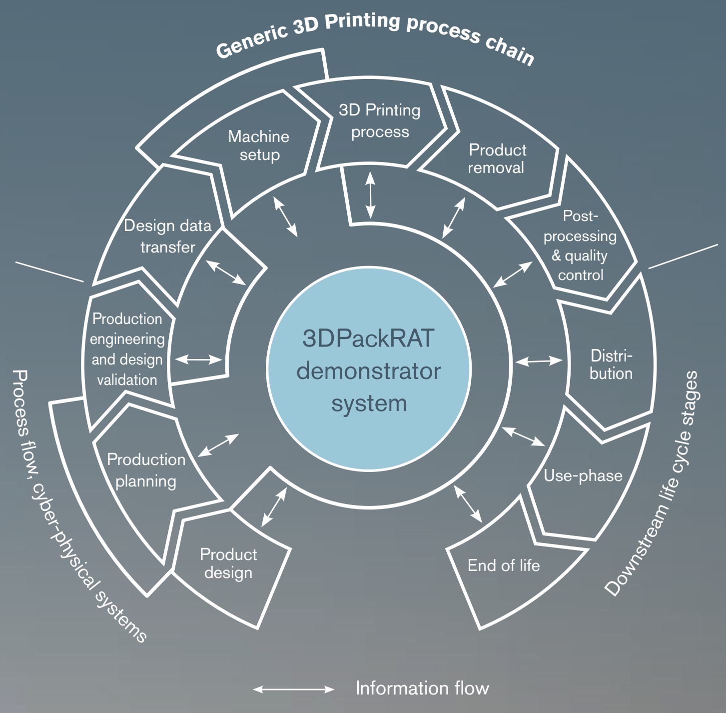

Figure 1: Scope of the demonstrator system in the overall process flow of 3DP.

Developing an integrated computational approach

Starting from the assumption that a joined-up process is more likely to deliver an efficient outcome, this project aimed to demonstrate the feasibility of an integrated approach to manufacturing execution in 3DP. Realising that overall cost minimisation will not be achievable by treating the build volume packing function and the scheduling task separately, the proposed approach is centred on the idea of joining up the production planning and machine setup functions.

The first element of this programme was thus to define a novel set of algorithms, heuristics and operational policies capable of delivering integrated optimisation. Building on previous work by Dr Martin Baumers, the project initially created a baseline algorithm by extending a voxel-based barycentric build volume packing technique to include a temporal dimension, capable of evaluating workflow configurations in four dimensions.

After beginning with the implementation of the demonstrator, the subsequent challenge was to devise a computational framework capable of handling a stream of manufacturing orders in the *.stl format by allocating these across multiple 3DP machines and multiple time periods. Having the ambition of transferring experimental computational approaches into a working implementation, the demonstration system was named the “3D Packing Research Application Tool” (3DPackRAT).

Financial and computational resource constraints dictated that a number of simplifications were made in the design and implementation of 3DPackRAT:

- build volume packing is optimised on the basis of geometric primitives rather than voxel representation,
- assumption of a fixed process takt time of one build operation per day and a time horizon of 5 days,
- reflection of only one variant of 3DP technology, choosing a state of the art commercial polymeric Laser Sintering system (EOSINT P100).

In the final element of the work performed, the computational approach was validated by a group of domain experts from the 3DP hardware, manufacturing execution software and 3DP service provision sectors. This validation activity led to considerable refinement of the portfolio of algorithms used by the demonstration system and to a general streamlining of the implementation.

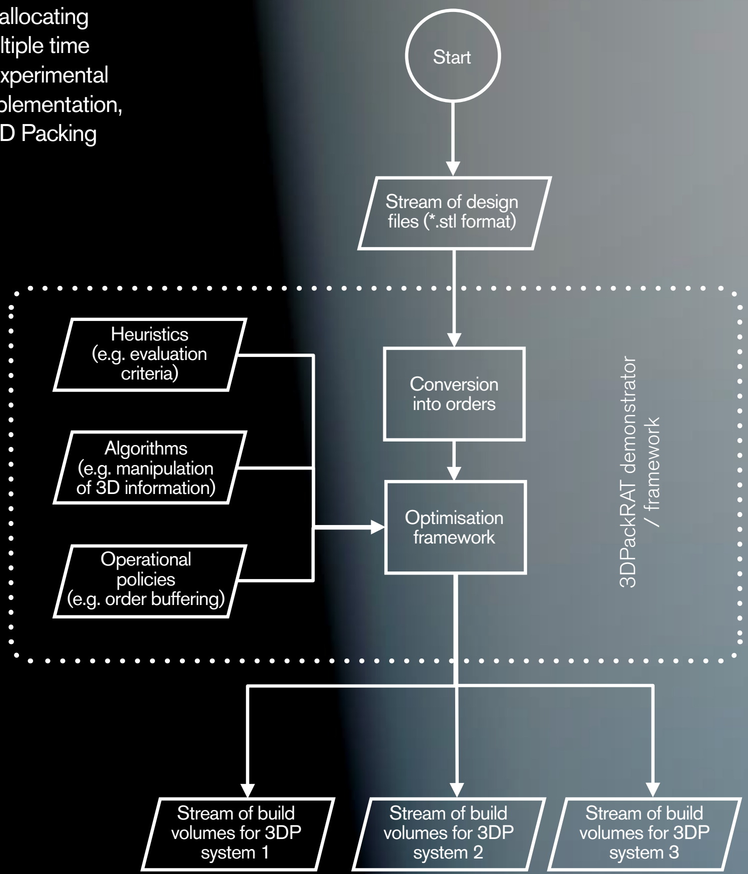

Figure 2: Overview of the 3DPackRAT demonstrator.

As snaphot of the implementation of the 3DPackRAT demonstrator.

Implementation

To develop a system capable of solving and demonstrating combined build volume packing and machine scheduling to address the identified capacity aggregation problem, several phases in the software development process were undertaken. Initially, the objectives of the project and input from industrial partners were used to realise a software requirements document outlining the requirements for the underlying pieces of software contributing to an extensible and modular 3DP workflow optimisation problem solver, and a web-based demonstrator tool.

Following this was the development of two main systems: a problem solver to address the 3DP workflow optimisation problem and a framework for exposing the problem solver as a web-based demonstrator tool. The process of developing both systems involved an iterative improvement design strategy, known as agile software development, where the development process would undergo several design-implement-test-improve cycles. By developing 3DPackRAT in this way, improvements and additional features realised through project meetings and interactions with industrial partners could easily be embedded into the framework. This permitted a realistic demonstration of the advantages of a combined packing and scheduling system.

The 3DP packing and scheduling system was designed to an interface/API which allows reuse of the problem-solving part of the system beyond a demonstrator tool. This approach allows the 3DP workflow optimisation problem to be tackled in a variety of ways combining different packing heuristics and scheduling algorithms.

The developed system is implemented as a standalone framework in Java. The Object-oriented design of the system, as shown in Figure 4, enables the use of multiple packing heuristics and scheduling algorithms within the system with opportunities to combine different 3DP machines, potentially even as a network of physically distributed setups, dynamic durations of time slots, and subject to other manufacturing constraints.

The demonstrator takes the form of a web application which allows the most recent version of the system to be used by providing updates from the server side and for the workload of the 3DP packing and scheduling system to be executed on the server. By taking this approach, the project collaborators can observe the most recent developments of 3DPackRAT and obtain valuable feedback throughout the development process. Ultimately, this led to the development of improved packing and scheduling algorithms to optimise realistic 3DP manufacturing workflow objectives.

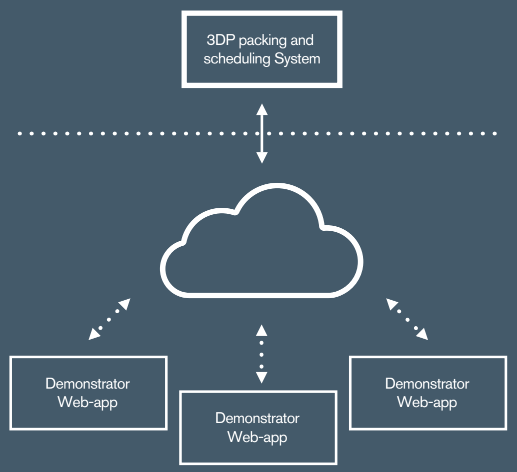

Figure 3: Visualisation of the software components making up 3DPackRAT.

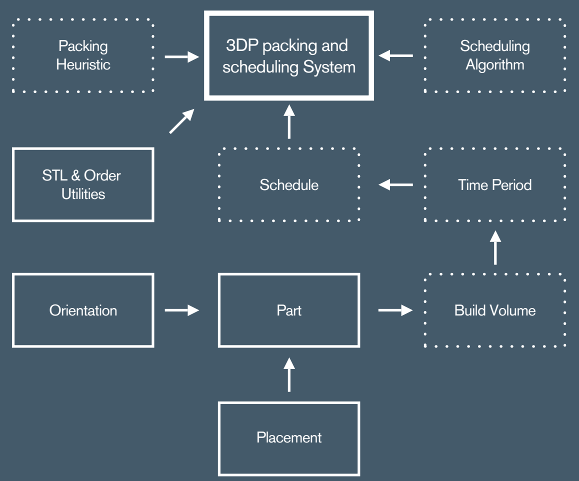

Figure 4: Simplified class diagram of the 3DP packing and scheduling System.

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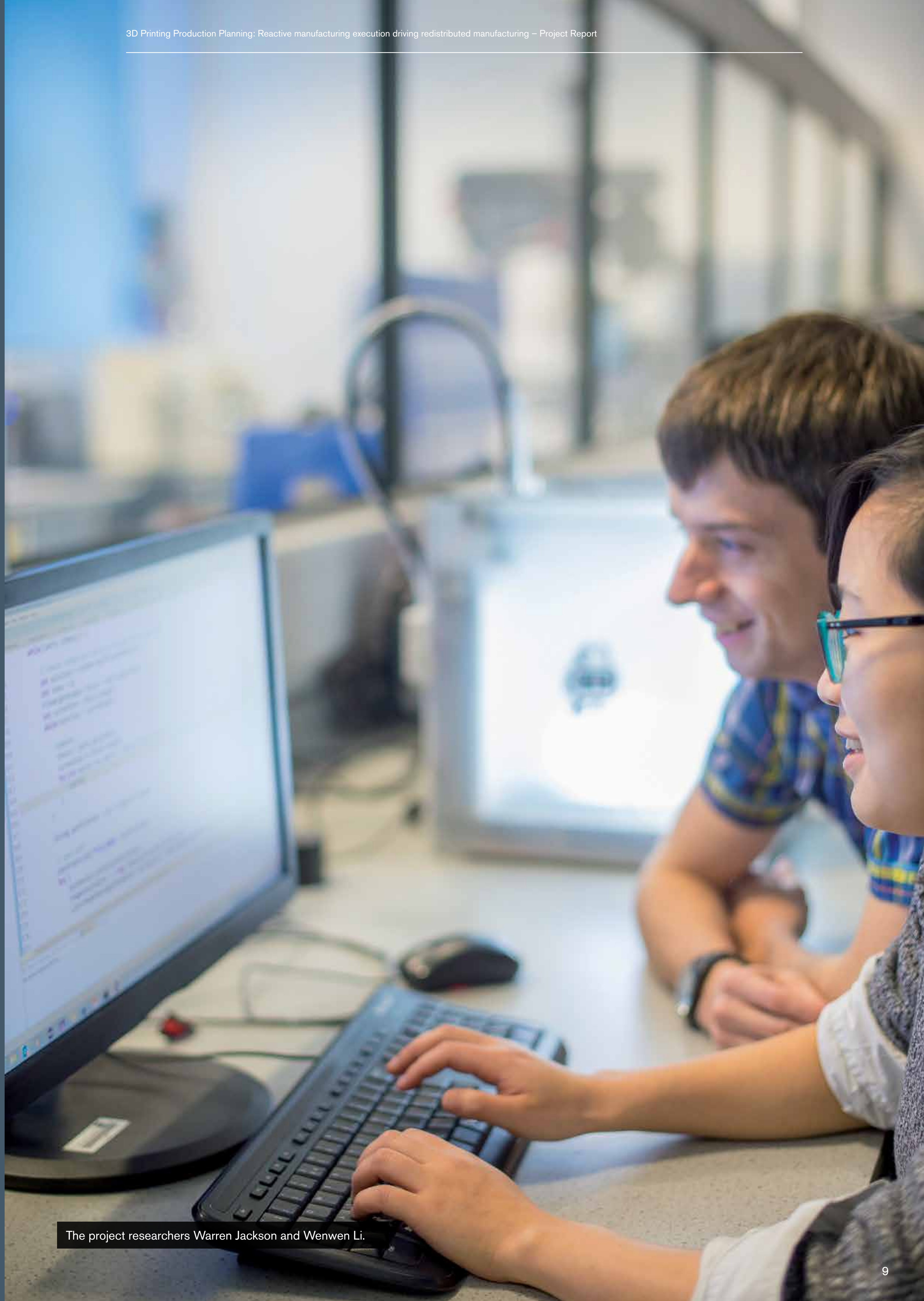

The project researchers Warren Jackson and Wenwen Li.

Summary of results

Forming a feasibility study, the core insight of this project is that the implementation of an integrated manufacturing execution system serving centralised and re-distributed 3DP systems is viable. Combining existing approaches to build volume packing and scheduling in an effective manner, the demonstrator system has generated well-specified builds and a dynamic allocation of orders to machines in which temporal factors, such as target dates, are weighed against packing performance. In industrial operation, such an approach to manufacturing execution should lead to lower cost and increased flexibility.

An interesting and timely insight arising from this project is that the single time period/single machine view of 3DP dominating the literature on the operational aspect of 3DP is simplistic. To reflect a realistic flow of orders, a multi-machine/multi-time period case is required, represented in the developed user interface as a $t \times k$ matrix covering t time periods and k systems. Additionally, the implementation of 3DPackRAT has shown that workflow optimisation tools can be extended flexibly to include additional systems. By increasing the number of connected 3DP machines, it is likely that the overall degree of efficiency achieved by the 3DP operation increases, resulting in supply side network effects.

From an implementation perspective, this research has shown that the computational strategy to address the large solution space of such combinatorial problems can be addressed in a highly parallel fashion. This promises very scalable overall systems. By basing such computational tools in the web, it is further possible for the developers to maintain and fine tune the implementation over time.

Moreover, 3DPackRAT has shown that specific requirements of products and characteristics of 3DP technology can be reconciled. Aspects such as physical location, machine status and condition, costs, product attributes, target dates and due dates can be handled as constraints in the integrated optimisation problem. Aspects pertinent to re-distribution that can be incorporated into such automated decision making include distance to the customer, local materials availability, energy supply and potentially also local risk factors that may lead to process disruption, e.g. labour disputes.

The presentations of the demonstrator given over the course of the project to 3DP service providers have shown that, despite utilising a bounding-box approach for packing and thus not allowing nesting, 3DPackRAT promises to outperform current rigid “train-schedule”-style operations of 3DP. A further aspect that was noted as positive by industrial partners is that by effectively optimising the workflow part-by-part, the integrated approach will also allow the seamless joining of prototyping and manufacturing workflows. In separation, such order streams considerably complicate the conventional (human-based) coordination of 3DP systems.

The project team discussing Laser Sintering technology (from left to right): Dr Ender Özcan, Dr Jason Atkin, Warren Jackson, Wenwen Li, and Dr Martin Baumers.

Conclusion

3DP presents an opportunity for flourishing supply chain innovation, including the emergence of highly re-distributed configurations. Current practise, however, routinely incorporates fragmented decision making, often without assistance from computational tools. To address 3DP manufacturing execution in this context, our project has generated an implementation demonstrating the feasibility of integrating computational build volume packing and scheduling systems. At this point, such functionality is commercially available only as separate systems.

This aspect fits into a general pattern in the evolution of information processing systems. In the beginning, software systems often resemble insular solutions, serving more or less as aids to human workers. Over time, information systems tend to form integrated structures, capable of handling large and rapidly changing amounts of information. The information systems serving 3DP do not form an exception from this. In the short run, commercially viable systems containing functionality similar to the 3DPackRAT demonstrator will provide a new kind of manufacturing execution solution which may be labelled a ‘capacity aggregator’ for 3DP.

As the main output of this research, the 3DPackRAT system has been presented over the course of the project to a range of industrial collaborators. Implemented as a web-based system, it is able to serve as a minimum viable product which can be used by interested parties for evaluation. Further iterations of the tool will be created in a rolling fashion and the project team will retain full control over the demonstrator system. More information on the project and 3DPackRAT is available at the project website at www.3dpackrat.com.

The project team expects that novel types of manufacturing information platforms will emerge to coordinate the various elements of the general digital manufacturing work flow. It is expected that over time, more and more elements will be integrated into optimisation systems. Regarding the manufacturing execution systems for 3DP, such as the developed demonstrator, it is expected that business platforms will emerge to orchestrate the order flow in 3DP by aligning network capacity towards low cost and also redistribution.

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