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Visual Analysis of Advanced Manufacturing Simulations

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Abstract

Today's manufacturing companies are faced with requests for highly customer-specific products that come in numerous variants but small numbers of units per variant. Therefore, their manufacturing processes need to be flexible and versatile. This opens up opportunities for real-time process planning, yet there is insufficient tool support for process planning that is not done days or weeks in advance. As a result, there is little incentive to collect process data on site. We describe a visual analysis tool that uses advanced manufacturing simulation to evaluate and optimize flexible manufacturing processes.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications; I.6.6 [Simulation and Modeling]: Simulation Output Analysis

1. Introduction

For years, the effects of global competition and technological advances have been changing the way western manufacturing companies work. Modern manufacturing processes are expected to be not only cost-effective but also flexible and adaptable. Manufacturing companies are in constant interaction with a changing environment. Order situation, raw material prices, legislature, and available technology all influence the ideal strategy of a market participant. As a consequence, there is not a single, optimal setup for a production process. For best results, the process needs to be constantly adapted to the current situation. Next generation factories will have to make extensive use of digital and virtual tools to ensure their flexibility and adaptability. Even though the digital factory has developed well past the stage of a mere vision, production plans are still made days to weeks in advance. The capability to make changes in product configuration or order priority on short notice is very limited. In a complex production system, making even slight changes in the production plan without extensive verification and replanning is not a decision taken lightly. Unforeseen deadlocks could cause significant delays and cost, mixing up items in the middle of the process could render an entire batch of products unusable.

Thomas and Kielman list the application to the manufacturing domain as one of the challenges for visual analytics [TK09]. Visualization and simulation could surely provide tools that facilitate understanding the current state of a complex process and the possible consequences of modifications. They could help to monitor the "health" of a process, point out potential problems, and identify opportunities for optimization. In spite of that, modern techniques of visual analytics are rarely applied to the manufacturing domain. Instead, processes are usually monitored using statistical methods such as statistical process control (SPC) and key performance indicators such as the overall equipment effectiveness (OEE), complemented with diagrams and reports. One challenge in the development of visual analytics tools for manufacturing is that, in our experience, real-time process data is not readily available. While trade secrets may be a factor, we think that with the unavailability of valuable tools there is little incentive to collect such data. This has been our motivation to create a simulation engine for an advanced manufacturing process, which we will use to develop and evaluate visual analysis tools for next generation manufacturing.

The flexible manufacturing system we are simulating is the iTRAME system (intelligent Transformable Assembly and Manufacturing Equipment) [RKK*07]. iTRAME is a prototype platform for a flexible material flow in a serial production with many variants and small batch sizes. It consists of modular elements that have standardized connectors and can be combined in various ways. Each element contains a two-level conveyor belt, making the elements bidirectional.

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Elevator segments can move work pieces between the two levels and switch segments can route work pieces on different tracks, creating a production network rather than a linear production line. The modularity of the iTRAME system greatly reduces the cost of process layout changes, making frequent layout changes more viable. This in turn creates a need for tools to assess the quality of a certain layout. Layouts may be ranked according to a number of different factors. The factor we focus on in this work is the total time it takes to manufacture a batch of products and our main concern is finding a layout that avoids congestion and thus unnecessary wait time.

2. Related work

The importance of visualization in manufacturing simulation has been discussed in [Roh00]. Rohrer names five benefits of visualization and animation for simulation: Verification and validation, understanding of results, communication of results, achieving acceptance of the model, and achieving credibility for the simulation. As requirements for the visualization, he lists interactivity, realism (again to support the credibility of the model), performance, flexibility, and ease of use. [WBJ03] presents a taxonomy of visualization techniques for the manufacturing domain. In [DFG*05], the authors describe a concept for a discrete manufacturing system simulation which is supported by virtual and augmented reality to create an intuitive and understandable user interface.

Regarding the visualization of time-dependent data in general, [MS03] gives a taxonomy of such data and an overview of methods for visualizing data over time, including multivariate data, animation, and event-based visualization. The authors point out that the latter plays an important role in the field of simulation, because it allows to present the data for effective analysis and to interact with the simulation in real-time. The SimVis tool [Dol07] is a system for the visual analysis of flow data resulting from computational fluid dynamics simulation. It contains various views that visualize the time-dependent result data and support the selection of data elements with linked views and brushing. Similarly, [DH01] combined a 3D volume visualization, scatter plot, and a histogram to visualize time-dependant, spatial data and supported the definition of a continuous degree-of-interest function using smooth brushing. [PBK10] presented an interactive visual approach to the validation of regression models for the development of car engines using a variety of different visualizations.

Aside from visualization efforts, [SSR00] demonstrated the simulation of complex assembly processes using a general purpose simulation language. The authors discuss the requirements of simulation models and give a detailed description of how they solved some of the problems they encountered while creating their simulation model of an assembly line.

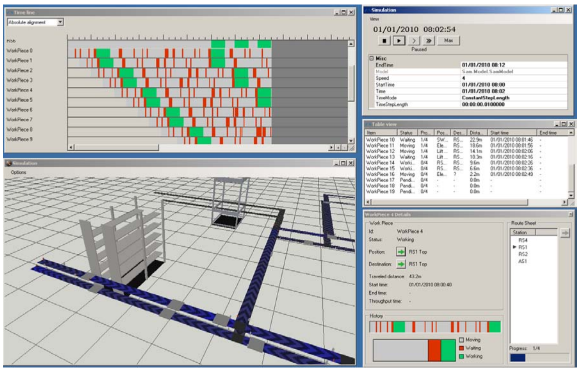
3. Simulation

On an abstract level, a manufacturing process is a transformation of work pieces from a raw state into a finished state. The transformation steps are carried out by machines and workers at certain locations in the factory. Work pieces and any needed parts and resources move between these locations in what is called the material flow. In our data model, we construct the manufacturing environment out of simulated iTRAME elements.

Each work piece has an associated route sheet, an ordered sequence of tasks that have to be performed on a work piece in order to transform it from its current state into its finished state. In a flexible manufacturing environment, route sheets may be revised and updated even after the work piece has been released into the process. In our case, all work pieces start out in an automatic storage element, which also appears as the last item on their route sheet, prompting their return there once they are finished.

4. Visual analysis

We provide a number of different displays for the analysis of a simulation run and its results (Figure 1). The spatial display shows a very concrete representation of the process layout and the work pieces moving through it. The table and time line views are more abstract displays for an analysis of the current situation that focuses on machines and work pieces rather than the spatial layout. Detail views can be used to inspect single machines or work pieces more closely.



Misc

EndTime 01/01/2010 08:12
Model Sam.Model.SamModel
Speed 4
StartTime 01/01/2010 08:00
Time 01/01/2010 08:02
TimeMode ConstantStepLength
TimeStepLength 00:00:00.0100000

Item	Status	Pro...	Pos...	Des...	Dista...	Start time	End time
WorkPiece 10	Waiting	1/4	SW...	RS...	22.9m	01/01/2010 08:01:46	-
WorkPiece 11	Moving	1/4	Ele...	RS...	18.6m	01/01/2010 08:01:56	-
WorkPiece 12	Moving	1/4	Lift ...	RS...	14.1m	01/01/2010 08:02:06	-
WorkPiece 13	Waiting	1/4	Lift ...	RS...	10.3m	01/01/2010 08:02:16	-
WorkPiece 14	Worki...	0/4	RS...	RS...	9.6m	01/01/2010 08:02:26	-
WorkPiece 15	Worki...	0/4	RS...	RS...	6.6m	01/01/2010 08:02:36	-
WorkPiece 16	Moving	0/4	Ele...	?	2.2m	01/01/2010 08:02:49	-
WorkPiece 17	Pendi...	0/4	-	-	0.0m	-	-
WorkPiece 18	Pendi...	0/4	-	-	0.0m	-	-
WorkPiece 19	Pendi...	0/4	-	-	0.0m	-	-

Id: WorkPiece 4
Status: Working
Position: RS1 Top
Destination: RS1 Top
Traveled distance: 43.2m
Start time: 01/01/2010 08:00:40
End time: -
Throughput time: -

Station
RS4
▶ RS1
RS2
AS1

Progress: 1/4

Figure 1: *Various tools for the visual analysis of the simulation progress and results.*

4.1. Spatial display

Despite obvious drawbacks such as occlusion and perspective distortion, we implemented our spatial display as a 3D representation of the situation. A simple 2D top-down projection would occlude the entire lower conveyor belt level and would therefore require some way of side-by-side presentation of the two layers, with special handling of elevators and switches.

We visualize the average work piece density on the conveyor by painting the belts in different shades of blue. The intensity of the colouring represents the average work piece density at that position during the period of time simulated so far (Figure 2)). To measure the density, we divide the conveyor system into short sections and divide the number of time steps in which each section was occupied by the total number of time steps simulated so far. Since this will result in very small values for most sections of the conveyor, we base the colour intensity on the square root of this density value. To draw the user's attention to the most frequented sections, we display red halos on the floor around these areas. This visually highlights those parts of the network that have a lot of work pieces passing through them or that cause significant delays in the material flow. These sections would be good starting points in the search for bottlenecks. It is also apparent which parts of the conveyor belt remain dark and are thus rarely frequented by work pieces. This might prompt refinements to the conveyor layout or route sheet strategy.

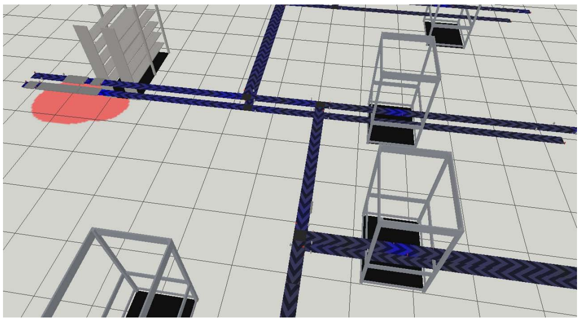


Figure 2: *The original infrastructure shows significant congestion in front of the elevator at the automated storage (bright blue segments and red halos).*

In Figure 2, blue spots inside the cubicles mark the work positions of robot stations where work pieces spend some time while they are being worked on. These are rather productive delays that could only be reduced by optimizing the machines. At the automatic storage on the top left, there are several bright blue spots that indicate significant delays. These are caused by finished work pieces queuing up in front of the elevator at the left, waiting for the automatic storage element to remove all items from the conveyor. Another cause is the general layout of the conveyor, which places every robot station on a conveyor arm on its own. This means work pieces travel to one of the stations, move to the lower belt, travel all the way back to the elevator next to the automatic storage to be lifted back up to the upper belt, and then start their way to the next robot station. This obviously bad layout causes significant congestion along this central arm. Based on this discovery, we can improve the layout by placing some of the arms to the left of the automatic storage and adjusting our route sheet strategy to distribute work pieces to both sides.

4.2. Time line view

The spatial view is complemented by other, more abstract views, which relate information to the object they refer to rather than a location in space. One view shows a time line of the simulation run (Figure 3). The top portion of the display lists the six robot stations of our example layout. Green bars indicate the time this station spent working on a work piece. The spaces in between indicate machine idle time. This kind of diagram is used in machine scheduling and is familiar to process planners. The lower portion visualizes the life cycle of each work piece. Green segments indicate the time this item spent in a robot station. Grey segments indicate travel time. The red segments represent the time this work piece was ready to move, but had to wait. Many short delays are caused by elevators as well as switches and machines, which stop work pieces for a short time to determine their identity. We have chosen the colours red and green for their clear semantic connotation but used a bluish shade of green to account for users with colour vision deficiencies. The user can switch between an absolute time scale and a relative time scale that left-aligns the beginning of all work piece lifecycles, allowing for easier direct comparison. It is possible to zoom in and pan through the data using the scrollbars and zoom buttons.

Figure 3, which displays the result before the optimization, shows that as the process progresses, there is a build-up of wait times between work steps 2 and 3 and for later items even between work steps 1 and 2.

4.3. Details view and user interaction

Selecting a machine or work piece in any of the other views will open an appropriate detail view (Figure 4). This shows the current status as well as a status history and relative time distribution. The work piece details view also displays the current route sheet, the current position and current destination. Clicking one of the arrow buttons takes the user to the corresponding position in the spatial view. Hovering over a section of the status history shows the time of the status change and the work piece that was processed or the machine at which the work piece was being worked on. Clicking takes the user to the respective work piece/machine.

5. Preliminary domain expert feedback

We demonstrated our work to a domain expert from a major automotive manufacturer and asked her for an informal assessment of the applicability and usability. She saw considerable potential for the development of tools that support

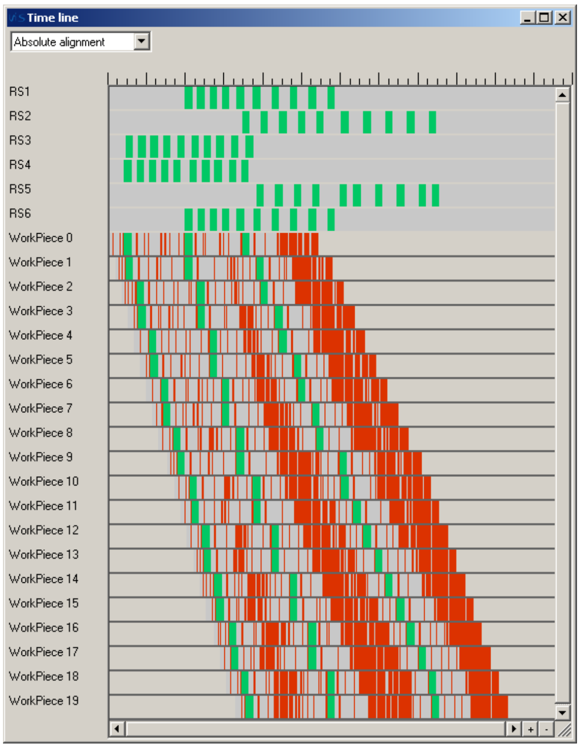
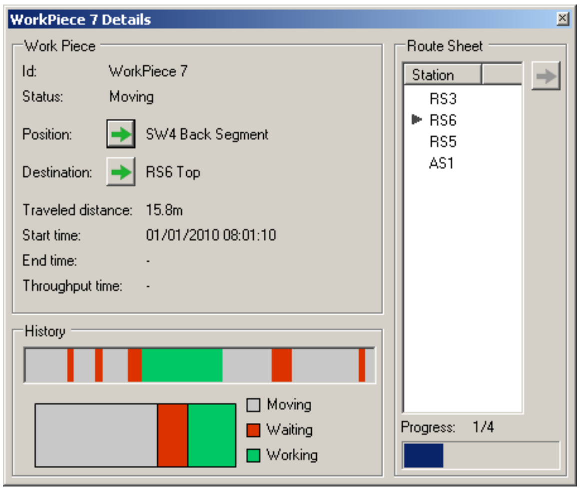


Figure 3: *Machine schedule and work piece life cycles of the original infrastructure. Green: working, grey: travelling, red: waiting.*

real-time planning and replanning. In her experience, production processes are currently simulated only in advance, resulting in diagrams similar to the upper part of Figure 3. These results are then used to optimize the sequence of production steps once before the production is started. She was not aware of any tools in use that would visualize simulation results as in Figure 2 and said this would contribute to a better understanding of processes.

6. Summary and future work

We presented and demonstrated our work on the visual analysis of advanced manufacturing simulation. We intend to add and evaluate more visualizations in the future. In the long term, we would like to connect to an actual iTRAME system and use our tools to supervise and optimize a manufacturing process on site, possibly extending the physical system with virtual, simulated elements.



Id: WorkPiece 7
Status: Moving
Position: SW4 Back Segment
Destination: RS6 Top
Traveled distance: 15.8m
Start time: 01/01/2010 08:01:10
End time: -
Throughput time: -

Station
RS3
▶ RS6
RS5
AS1

Progress: 1/4

☐ Moving
🟥 Waiting
🟩 Working

Figure 4: *The work piece details view shows various information and statistics on a single work piece.*

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