Manufacturing Process Simulation in a Hybrid Cloud Setup

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Abstract: Model-based design of manufacturing robotic systems involving the usage of different tools, models and the co-simulation of the system behaviour benefits from collaborative platforms enabling ready-to-use and cloud-hosted tools and models. Nonetheless, due to market segmentation and the difficulty to deploy and support all the existing tools and models in such a platform, it is, therefore, reasonable to consider a hybrid cloud-setup where some tools run in the public cloud and other are only available in private clouds or dedicated machines behind the walls of the licensed institution. In this paper, we report on a experiment of such scenario, where a Matlab/Simulink^{TM}, LS-Dyna, and Model.CONNECT^{TM} powered co-simulation tool suite running in a private cloud is combined with the DDD Simulation tool running inside a public cloud. Due to this setup it was possible to combine a 1D hot stamping process simulation with a 3D visualisation. Finally the results of the process simulation were improved by considering realistic movement of the robot. Our study elicited several limitations and feature requests that need to be addressed to better support a hybrid cloud setup for model-based design practitioners. We expect this initial contribution to trigger ground breaking research encompassing all the community members interested in hybrid co-simulation setups.

1 INTRODUCTION

Systems gathering physical information through sensors from the real world, processing them digitally and autonomously affecting physical environment are increasingly important in today's world. These systems are called Cyber-Physical Systems (CPSs) and are widespread in several industries, from transportation to smart cities and from smart manufacturing to agriculture. As a consequence, manufacturers, already constrained by the need to provide a huge variety and quantity of products, have also to embed such systems in their products, making them smart and connected (Porter and Heppelmann, 2014). Today, the change of production systems is gradually becoming a need to sustain a position in the Industry 4.0 domain, driven by computation, automation and robotics, and declined in nine categories of innovative digital technologies (autonomous robots, simulation, horizontal and vertical system integration, IoT, cybersecurity, the cloud, additive manufacturing, augmented reality, big data analytics) (Rüßmann et al., 2015). Data and observation become the strategic key to support online decision-making in production systems reconfiguration (Braun et al., 2012; Hasselbring et al., 2019).

A significant adoption of computation in production is required enabling the achievement of the higher-levels of the CPS 5C (connection, conversion, cyber, cognition, and configuration) architecture (Lee et al., 2015). At this stage, systems optimise themselves and work at the full digital-twin level. As a consequence, models of the system at hand (i.e. Model-Based Design (MBD) tools, methods and competences) are required in manufacturing, also boosting the role of software in manufacturing composed by self-optimising CPSs and Digital Twins. Also logistics, integrated with production systems, have been strongly affected by digital technologies, presenting several applications (autonomous robots and vehicles, tracking and decision making systems, smart products and cloud-supported networks, real-time big data analytics), mainly gathered under the umbrella of Internet of Things (IoT), to control the

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inventory level, enhance information flows and defining products' optimal routing transport (Atzeni et al., 2021). Normally, production system lifecycle is composed by long development phases and is structured in sequential phases (conception and planning, design and engineering, construction, validation, verification and commissioning, use and disposal). In the development phase of the production systems lifecycle, it is common to run manufacturing simulations without simulating the properties of the material during each production step. On the other hand, it is state of the art to simulate the process during the production preparation phase (Wifling, 2021).

Model-based design and simulation are powered by development tools and different modeling languages, but it is expensive to invest in such technologies, because any reasonably complex system requires different models and tools making the MBD field a heterogeneous and challenging community (Robinson et al., 2021) for new adopters. Also, in some cases consortia of partners developing a model of a manufacturing process may have complementary expertise, tools and licenses, but the interaction needs to be orchestrated on a case-by-case approach. One solution to this problem is to deploy the tools in a single cloud environment, as the HUBCAP platform (Badicu et al., 2021), yet it is not possible to guarantee a complete coverage of all potential tools and models that an arbitrary user may need, thus a hybrid cloud solution where public cloud resources are used with additional private cloud machines is a possible alternative but not well analysed.

In this paper, we report on work towards analyzing the feasibility of hybrid cloud approaches. The results gathered during a feasibility study on a hybrid cloud approach to support a co-simulation of a metal hot stamping process experiment by two complementary partners. The process simulation was done in a local machine available only to one of the partners and the 3D simulation of the manufacturing was done in a cloud hosted tool. The combination allowed to fine tune the production parameters in the design phase of the production system; despite the fact that a suite of the tools for the co-simulation was hosted locally (unavailable to the other partner) and that the process involved manual data transfers. We expect our results encourage similar experiments by members in the manufacturing community, and that the hybrid cloud setup becomes a valid approach in future experiments with tool licensing issues.

The remainder of this paper is structured as follows: Section 2 introduces the background on the HUBCAP cloud platform. Section 3 describes the experiment, the modeled process and the joint co-simulation between tools in a private cloud and a tool in the HUBCAP cloud platform. Finally, Section 4 contains the result of our co-simulation results, Section 5 presents a discussion of the results, and Section 6 contains our concluding remarks.

2 SIMULATION IN HUBCAP

The methodology behind Model-Based Design eases the development of Cyber-Physical Systems (Fitzgerald et al., 2014). It prescribes the development of mathematical models of the system's components, which are then used to reason, test, and simulate the system behaviour in a agile virtual setup. Developing in a virtual setup is known to reduce costs and to elicit requirements and risks in shorter time, yet it is often the case that a CPS system under design is highly complex and encompasses multiple models developed in multiple tools.

Although a solution for coupling the different models exists since long time ago in the form of co-simulation, practice shows one faces several barriers for new MBD adopters, because the different models and tools usually run in diverse software environments, require advanced expertise and setups, and involve complex legal/licensing agreements.

To lower the complexity of potential adopters of MBD, the HUBCAP project developed a cloud-based platform (Macedo et al., 2021) featuring ready-made software environments, where providers prepare sandboxes (software environments, tools and models) that adopters can explore via their browser to "test before invest" with such models and tools at a lower cost of entry.

Sandboxes as defined in (Larsen et al., 2020) are composed of several virtual machine instances exposing a remote desktop connection via a web middleware, catering for the different software environments (Operating System, Libraries and other Dependencies) required to run tools and models. In addition, the middleware around the virtual machines enables several users to interact and collaborate with the prepared models and tool by featuring an "invite guest" button, that allows a sandbox owner to invite other users as guests to a sandbox environment facilitating discussion, training and demo sessions.

Figure 1 depicts the aspect of the sandbox webpage. In the middle the user can interact with a remote desktop of a virtual machine hosting the DDD Simulator by TTS-Technology Transfer System S.r.l. (a MBD tool used to provide solutions to manufacturing companies and used in the experiments reported in this paper). In the right-side we see some of the additional controls/buttons a user resources to while interacting with a sandbox.

Among the HUBCAP models and tools catalogue, the users find the INTO-CPS Application (Macedo et al., 2020), with its co-simulation engine (Thule et al., 2019), several models developed using the Vienna Development Method and its associated tool (Rask et al., 2020; Rask et al., 2021) the DDD Simulator shown in Figure 1, but the catalogue is far from covering the whole range of MBD tools. For instance, the Model.CONNECT^{TM} co-simulation platform and Matlab tools required for the experimental setup reported in Section 3 are not available in the platform, but are available and licensed for local usage inside the institutions leading the experiments. This situation challenges the HUBCAP platform and might hamper its wide adoption.

In addition, the HUBCAP sandbox concept was designed in the cyber-security practice, where different users' resources run in disjoint and tightly contained virtual machines ecosystems (operating system, storage, networks,...) to ensure a secure environment (Kulik et al., 2021). Nevertheless, in some cases, a user may be required to combine tools available in the public platform with tools running in a private local server or neither available nor licensed to run in the HUBCAP platform. For instance, in the experimental setup detailed in Section 3 requires the combination of a tool deployed as a HUBCAP sandbox and a tool running a on-premises Desktop. Such hybrid cloud setups are currently not a feature of the HUBCAP platform, and this work clarifies the limits and possible developments to support hybrid simulation setups.

3 EXPERIMENT

Our experiment joins tools in a local machine with a tool running in a HUBCAP sandbox that are used together to jointly produce a open-loop co-simulation of a metal hot stamping (press hardening) production process which consists of three stages:

- furnace - modelling the heating of the unformed metal plates,
- transfer - modelling a robotic manipulator moving the plates from oven to press,
- forming press - modelling the draw and quenching of the plate in the die.

The hybrid-cloud concept of the experiment is depicted in Figure 2, which highlights the dataflow between the public and private environments. The material properties of the metal sheets are simulated on a local PC while the 3D manufacturing simulations runs in the HUBCAP sandbox environment. The experiment was designed in that way for a simple reason: the vendors of the tools used for the process simulation are not part of the HUBCAP ecosystem. An open loop approach is followed due the fact that the Sandbox is an isolated (and secure) environment which does not support a direct API (application programming interface) interface. Nevertheless data can be upload and downloaded. Thus, the following procedure has been followed:

1. 1D process simulation on a local PC (origin of the use case) and upload of the results to the HUBCAP sandbox,
2. creating 3D - model of the manufacturing and simulation based on timing of the 1D Simulation,
3. adding logic and kinematics to 3D-model,
4. DDD-Simulation of manufacturing which results in new timing setting for the production steps,
5. adaptation of the process simulation according to DDD-Simulation,
6. fine tuning of the process parameters.

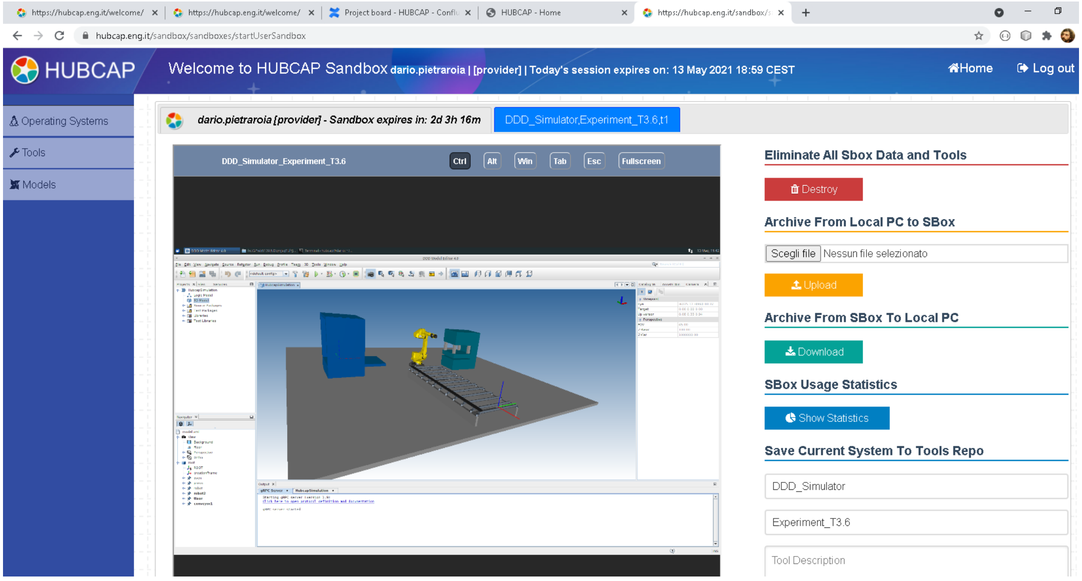
3.1 Process Simulation

The focus of the process simulation is the temperature and yield stress behaviour of the metal plates at each production stage. The simulation is based on existing models from Virtual Vehicle Research Gmbh (VV) and has been used for a digital twin simulation (Wifling, 2021):

- The furnace or oven model simulates the temperature increase of the plates and has as (production) parameters the oven temperature T_{oven}, number of slots and minimum duration time in the oven t_{min}
- The transfer corresponds to the movement of a robot which means a slow cool down phase for the plates. There is only the transfer time as parameter t_{trans}
- Finally, the forming press includes two steps: drawing and quenching which means a rapid cool down of the plates. A key parameter of the press model is the closing speed, which is actually not a fixed parameter but an input.

The calculation of the temperature is based on (Weiß, 2013) chapter 6 and (Weiß et al., 2013), while the calculation of the yield stress is based on a temperature dependent stress strain table.

Figure 3 shows the simulation setup using Model.CONNECT^{TM} as co-simulation platform. A Python script is used to create (virtual) ID's for the



hubcap.eng.it/sandbox/sandboxes/startUserSandbox

Welcome to HUBCAP Sandbox dario.pietraroia | [provider] | Today's session expires on: 13 May 2021 18:59 CEST

dario.pietraroia [provider] - Sandbox expires in: 2d 3h 16m

DDD_Simulator,Experiment_T3.6,t1

DDD_Simulator_Experiment_T3.6

Scegli file Nessun file selezionato

DDD_Simulator

Experiment_T3.6

Tool Description

https://hubcap.eng.it/welcome/
https://hubcap.eng.it/welcome/
Project board - HUBCAP - Conflu
HUBCAP - Home
https://hubcap.eng.it/sandbox/
HUBCAP
Home
Log out
Operating Systems
Tools
Models
Ctrl
Alt
Win
Tab
Esc
Fullscreen
Eliminate All Sbox Data and Tools
Destroy
Archive From Local PC to SBox
Upload
Archive From SBox To Local PC
Download
SBox Usage Statistics
Show Statistics
Save Current System To Tools Repo

Figure 1: Snapshot of the DDD Simulator tool running inside a HUBCAP sandbox environment.

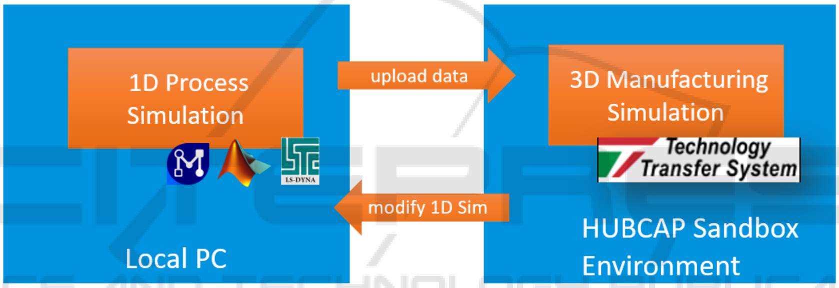

1D Process Simulation
LS-DYNA
Local PC
upload data
modify 1D Sim
3D Manufacturing Simulation
Technology Transfer System
HUBCAP Sandbox Environment

Figure 2: Hybrid cloud experimental setup: A local machine emulates on-premises private cloud hardware hosting Matlab/Simulink$^{\mathrm{TM}}$, LS-Dyna, and Model.CONNECT$^{\mathrm{TM}}$; the HUBCAP platform serves as the off premises public cloud infrastructure hosting the DDD Simulation tool; and the dataflow.

metal plates (source of the metal plates) in intervals of 15 seconds. The plates are taken by the oven model as soon as a free slot is available. Both, the oven and the transfer model are implemented in MATLAB Simulink. Another Python script calculates the closing speed of the press depending on the temperature after the transfer based on polynomial second order. Finally, the drawing and quenching is modelled in LS-Dyna. LS-Dyna uses finite element analysis to calculate the sheet temperature while the Simulink models are time based. The following co-simulation settings have been used:

- coupling time (interval of data exchange): 10ms (for all models)
- scheduling: sequential, with the following order: ID generation, oven model, transfer model, press model

The temperature and yield stress values of each step have been saved in csv format including a time vector. Also percentage status of the transfer and the position of the press over time has been saved in csv files. Figure 4 shows the results of the LS-Dyna model using LS-PrePost for visualisation. The stroke which is coming down to form the the plate is colored in red. The metal plate itself is colored in black (thin plane) and the form/shell for the final shape of the plate is colored in green.

3.2 3D Manufacturing Simulation

The first 3D environment realized for the HUBCAP project is a visualization environment that represents the results of the process simulation over time through an animation. The tool used to create the 3D simulation is DDDSimulator, a discrete event simulation software with integrated 3D environment and DES (discrete-event simulation) simulation, used to build simulation models of production and logistic facilities to simulate the system behavior and improve the performances of existing or new systems. The csv output files from the 1D model contain the time-series values of the variables representing the state of the process. While running, the simulation model refreshes the state of the system every 50 ms and parses all the input files updating the environment according to the new state. Some state changes affect the 3D environment while other, as the temperature of a plate or the yield stress of the plate inside the press are plotted on a dashboard. The 3D model consists of a sketched geometry for the oven and the press while a 6 DOF FANUC robot has been used to represent the transportation system. The oven contains 9 slots and in each slot one plate can be placed . Since there isn't any geometrical information about the oven, the position of the 9 slots are modeled as frames which identify the coordinates in which the plates are placed in space and each slot is placed approximately 100 mm over the other along the Z axis. The transfer information provided is the percentage of the movement from the oven: 0 means the plate just left the oven and 100 means that the plate arrived into the press. So, when the ID of a plate changes, the plate is moved from the oven to a pick position at the base of the oven. Then the plate is attached to the hand of the robot and the angle of the base joint if the robot is updated.

The input data read from the data flowing from the process model are:

- Creation of a new plate: each time a new sheet ID is generated, the model creates a 3D box representing the new plate,
- Plate ID for each plate in the oven: a file reports the id of each plate in each slot and plates are positioned at the corresponding position,
- Temperature of each plate in the oven: the temperature for each plant in the oven is plotted on a dashboard and the color of the plate changes accordingly,
- Transfer state: the transfer state is refreshed and the robot position updated,
- Press position: the z position press die is red and the position of the die is updated in the 3D model,
- The yield stress of the plate in the press is plotted on the dashboard.

To complete the interaction, a pure-simulation conveyor which carries away the worked plate has been added, this additional module doesn't depend on any parameter from the first simulation but moves the piece with a constant velocity. This first phase of the experiment worked as a proof of concept to interface the two tools through the HUBCAP platform.

To provide a more significant case, an experiment which combined the usage of the two simulations was created. In the new experiment, a kinematic model of the transfer between the oven and the press using the 6 DOF (degree of freedom) robot was created, the model is used to estimate transfer times. Figure 5 shows the 3D environment with the robot extracting a plate from the oven. The resulting values are then used as inputs by the 1D simulation model to evaluate the thermal characteristics of the process and the deformation of the metal sheet in the press. Such results can then be transfer back to the 3D simulation model and visualized in the 3D animation. The previous model didn't also take in account the approaching stroke of the press which is needed to bring the die in contact with the plate, once the metal sheet was put into the press the process started instantly. In the kinematic model an approaching stroke was added to simulate the additional operation and thus the additional transfer time for the plate.

4 RESULTS

Although the process involved manual steps to transfer data between the tools, the open-loop co-simulation of the metal hot stamping process using the hybrid cloud setup was feasible and in the following we highlight the improvement achieved by the combination of the tools.

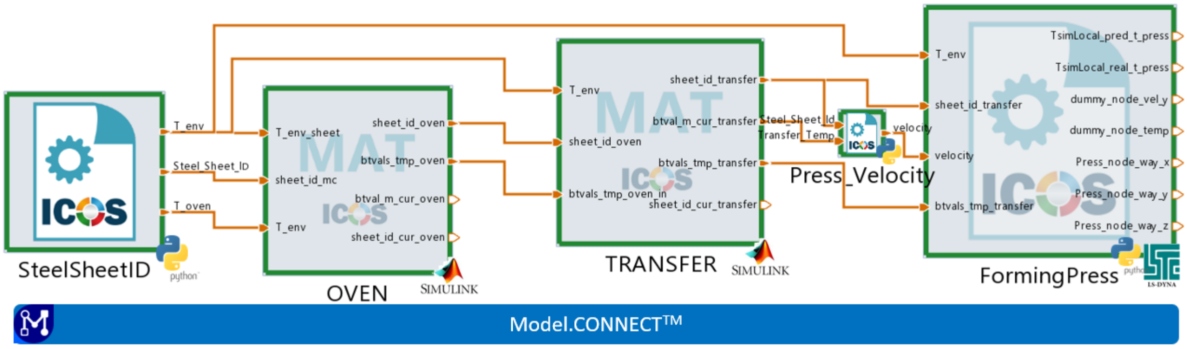
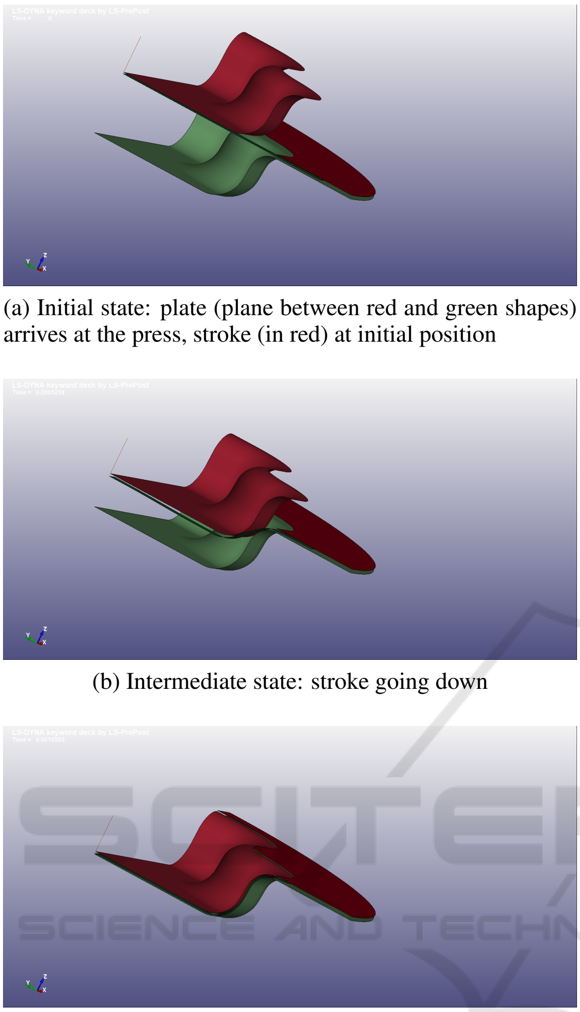


Figure 3: The connection diagram for the different components of the co-simulaton.



(a) Initial state: plate (plane between red and green shapes) arrives at the press, stroke (in red) at initial position

(b) Intermediate state: stroke going down

(c) Final state: final stroke position, sheet forming process finished

Figure 4: Press states calculated by LD-Dyna and visualized in a post process using LS-PrePost.

4.1 Process Simulation

Figure 6 shows a comparison of the temperature traces of the initial simulation (step 1 according to the enumeration in section 3) and the adapted and fine tuned simulation (step 6) at each production stage. New sheets are create in intervals of 15 seconds, which is the bottleneck in the initial simulation since t_{trans} was assumed with 5s. However, the DDD-Simulation showed that a realistic movement of the robot from the oven to the press takes 14 seconds plus 3 seconds more for grasping (see table 3), which means a new sheet can be taken after 34s. That new bottleneck can be clearly seen in the figure. While the start-up phase (time span till all oven slots are occupied) is the same for both simulations it can be seen that the throughput f_{tp} is much lower in case of the adopted simulation.

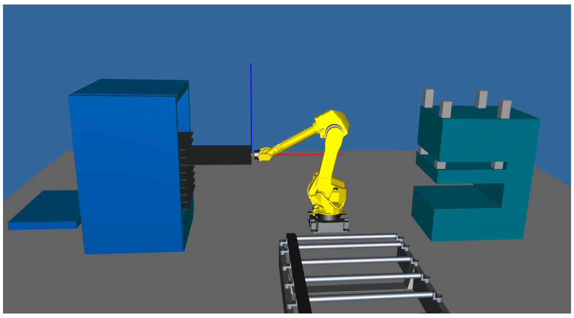


Figure 5: 3D simulation with kinematic simulation of transfer.

Figure 7 shows a one to one comparison of a single sheet after the startup phase (time shifted to zero for comparison purposes). The first row shows the sheet temperature trace for all production stages while the seconds one shows the yield stress. In case of the adopted simulation (dashed) it can be seen that the sheet remains much longer in the oven, while in case of the initial simulation it remains for the minimum time of 150s. Another consequence of the increased transport time is that T_{oven} had to be raised to 850°C in order to reach more or less the same final yield stress value at the end of the production. The change of the oven temperature belongs to the fine tune step (step 6). The results of the adopted and fine tuned results can be displayed again in the 3D simulation.

Table 1 gives an overview of the simulation parameters and table 2 shows how long it takes to create one piece t_{sheet}, the throughput for an hour f_{tp} after the start up phase and the final yield stress value σ_{final}.

Table 1: Simulation parameters.

	T_{oven}	t_{min}	slots	t_{trans}
	$°C$	s		s
initial sim	800	150	9	5
modified sim	**850**	150	9	**17**

Table 2: Performance and outcome (steady state).

	t_{sheet}	f_{tp}	σ_{final}
	s	pieces/h	MPa
initial sim	157.4	240	197.8
modified sim	341	61	181.1

4.2 Visualization of Results from 1D Simulation

As previously stated, model based design techniques often involve the usage of multiple tools and involves different expertises. The dynamic visualization of

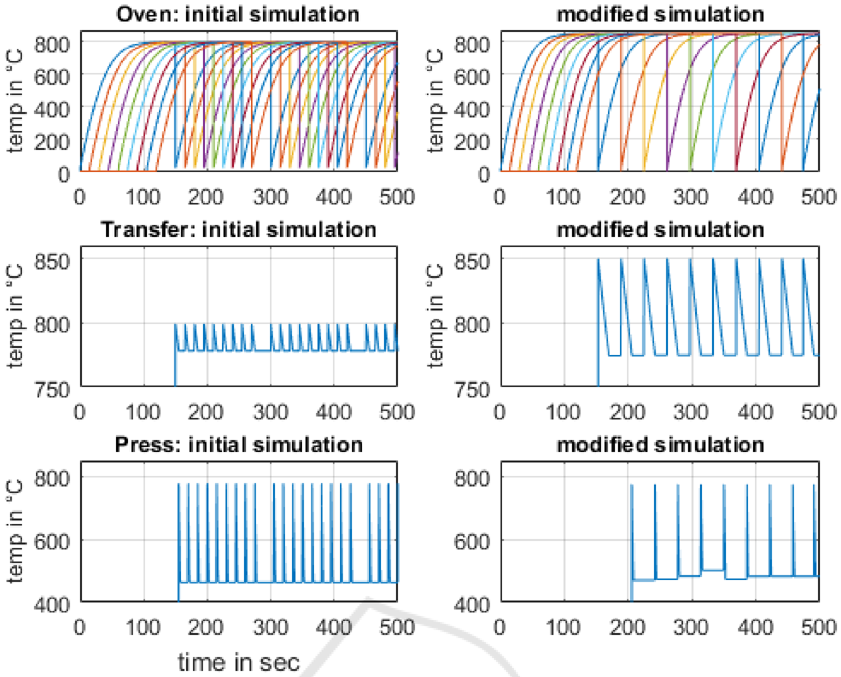


Figure 6: Comparison of the process simulation: the left column shows the initial simulation while the right column shows results of the adapted and fine tuned simulation. First row: the temperature values of the metal sheets at each slot of the oven. The second row: temperature decrease of the metal sheets during the transfer. Last row: the temperature trace of the sheets during stamping.

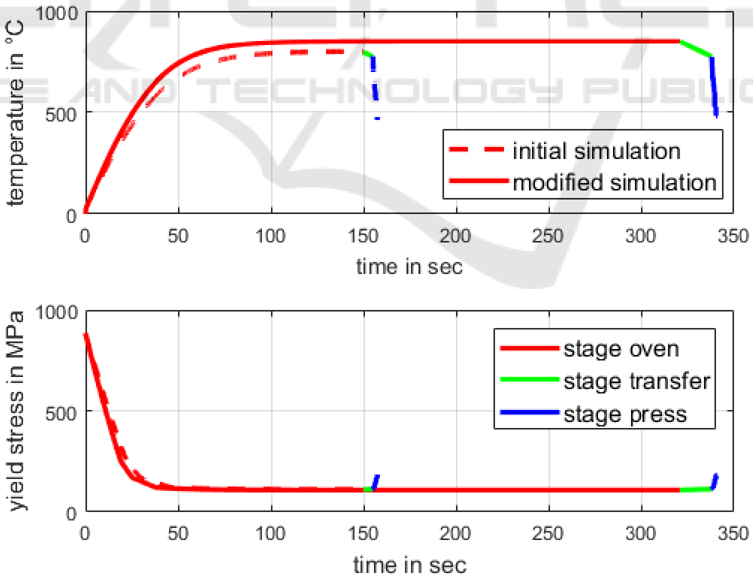


Figure 7: One to one comparison of a single sheet: the dashed line shows the trace of the initial simulation while the continues line shows the trace of the adapted and fine tuned simulation. The different colours of the sections indicate the current production stage.

the results of process simulation evolving over time inside a sketched 3D environment greatly helps the analysis. In the case of our experiment, one was able to follow the evolution of temperature parameters and yeld stress for all the plates in the system. The analysis perfrormed by both experts of material process simulation and DES event expert simulation was the basis for the second part of the experiment.

4.3 3D Kinematic Simulation of System

The use of 6DOF kinematics simulation allowed to better estimate the transfer times. Table 3 shows the resulting moving time for different phases of the process, the resulting interval became the new transfer time data.

Table 3: Times for each phase of transfer operation.

Movement phase	(s)
extraction from oven	3
transfer to intermediate position	6
transfer to press	2
move to safe position before press starts	3
press rapid stroke	3
Total	17

The model also allowed to study the time that the plates are stored in the oven, table 4 shows that the system reaches a steady-state state for the heating time after 10 plates.

Table 4: Oven time during ramp up.

plate_id	oven_time (s)
0	153
1	173.998
2	194.996
3	215.994
4	236.992
5	257.99
6	278.988
7	299.986
8	320.984
9	320.982
10	320.982
11	320.982

For the purpose of designing the production line, the model shows that the bottleneck is the robot, since it's used both to load and unload the press. A possible solution to increase the productivity would be to use another robot to unload the press, this could allow not only an increase of the throughput but also some energy saving reducing the oven temperature and the new temperature could be estimated using the process simulation.

5 DISCUSSION

The 1D process simulation is an abstract simulation of the production. Figure 6 shows indeed important material properties of the manufacturing stages but it is not really easy to understand what happens, while a 3D animation gives a much better impression. By simulating a 3D model of the production line and displaying the results of the 1D process simulation both kind of simulation have been combined. The first 3D simulation was purely based on the 1D results, allowing the audience easily to follow the manufacturing steps and to see the impact on the material properties of the sheets. However, this was done without considering the kinematics of the robot.

The simulation has changed from a pure visualisation to a DDD-simulation by adding logic and kinematics's to the 3D model. It turned out that the assumed transfer time of 5 seconds was not a realistic parameter value in the initial process simulation. As a consequence the robot becomes a bottleneck in the production and the throughput decreases significantly to 25% of the initial simulation. Moreover, going back to the process simulation and adapting the the transfer time parameter showed that the final yield stress values was not satisfyingly anymore due to the temperature decrease during the transfer. Thus, the oven temperature had to be raised.

Another aspect of the demonstrated use case is the collaboration between VV and TTS. Data generated by VV could be easily uploaded to the shared sandbox, where TTS further proceeded it by simulating a 3D environment. Moreover, TTS added it's own simulation logic and kinematics which in turn, changed relevant simulation parameters for the process simulation. Finally, VV had to fine tune the simulation and generated again new data for the 3D simulation.

6 CONCLUDING REMARKS

In this paper, we report on a experiment of a combination of co-simulation tools running in a hybrid cloud setup. The locally licensed Matlab/Simulink^{TM}, LS-Dyna, and Model.CONNECT^{TM} powered co-simulation tool suite was hosted on-premises and combined with the DDD Simulation tool running inside a off-site cloud. The experiment shows the combination is feasible and enables the production and improvement of co-simulation results in the cases where licensing issues require a hybrid cloud approach. Moreover our study provides evidence of the feasibility of such hybrid cloud setups in supporting model-based design. Nevertheless, there are known drawbacks/challenges associated with hybrid cloud setups, mainly due to the fact that those setups involve different institutions, and we confirmed some of the challenges, in particular we were required to introduce manual steps to perform dataflow, which would be easy to automate in case the experiment was completely hosted on-premises. To realize the full potential of a hybrid cloud co-simulation solution based on the HUBCAP platform the following need to be addressed in *future work*:

First and foremost, automated orchestration of the cloud environment via an API or a federated cloud approach where users can add their private resources as computation nodes (virtual machines) to a particular HUBCAP sandbox would ease the dataflow of our experiment that could be automated instead of a manual data iteration (upload new timing settings from a configuration file, run experiment, download result...) Also, the improvement of intellectual property protection and licensing makes the platform more suitable for adoption by industrial partners. The co-simulation data and environment shared between TTS and VV was protected under existing contractual agreements between the two partners. To be useful, the coupling of the private resources and hybrid cloud should also be available to be used by other partners in the MBD community without any legal binding. Both by guaranteeing the privacy of the platform user data and by allowing external partners to host their IP protected components locally.

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