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ENHANCING PRODUCTIVITY USING OFF-LINE PERFORMANCE MODELLING

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Abstract

The available literature associated with virtual manufacturing is extensive. Far fewer publications have been sourced for virtual techniques associated with specific manufacturing functions, such as metal punching.

A novel punching press work-cell has been developed that incorporates many innovative features, based around continuous production using coiled metal. The punching system within the overall work-cell has such a high productivity that problems associated with material handling, in particular, at the output side of the system became apparent. A collaborative project was initiated between an Australian university and the manufacturing and design organisation to investigate and ameliorate these problems.

The existing work-cell prototype was decomposed into functional systems to provide a functional analysis of the overall design and to better understand the synergy between mechanical, power electrical, electronic and computer control. This investigation into synergies resulted in the identification of three alternatives to improve overall work-cell performance:

1. Replace the decoiler electrical motor, controlled by an inverter drive, with a servomotor.
2. Develop and implement an improved control architecture for the catenary system.
3. Develop an off-line simulation of the work-cell to better understand the behaviour of the catenary system when work-cell systems parameters are changed.

This paper reports on the systematic approach taken to identify opportunities for enhancing productivity of the work-cell and, specifically, the processes used to design, evaluate and implement an off-line simulation for the prototype work-cell.

Keywords: design of automated systems, simulation design, integration, mechatronic design

1. Introduction

The available literature associated with virtual manufacturing is extensive. Far fewer publications have been sourced for virtual techniques associated with specific manufacturing functions, such as metal punching, for example:

- Virtual processing of punching and laser cutting of thin metal sheet with comparative estimates of processing time for both processes between the virtual and practical machine using a custom developed scheduling. The work sought to find optimum sequences of parts in short batch production [1].
- A proposed virtual manufacturing approach for designing, programming, testing, verifying and deploying control systems for agile modular manufacturing machinery [2].

- Experiments undertaken to determine metal sheet forming stability during stamping of complex three-dimensional sheet metal parts, principally investigating in-plane compressive stresses [3].
- Studies to verify that the integration of computer based technologies could be effectively applied to various metal forming processes to reduce lead-time and process cost [4].

The focus of this paper is a case study associated with the simulation of material handling the material handling of metal strip in an integrated fashion with the associated processing machine (metal punching). A significant functional issue is that associated with the input side of the processing machine, where a catenary system is used to accommodate variations between the decoiler and punching machine. Although a common technique practically, few publications have investigated its enhancement, for example, [5] investigated alternative catenary control methods for a strip annealing furnace input (i.e. load cells mounted on rollers; laser and camera systems; and, pulsed radar detection), all of which are of high cost with functional drawbacks. The catenary control system described in this paper is based on a long-range position sensor, a low cost solution.

2.1 Simulation case-study

A principle objective of computer simulation has been designed to assist in determining suitable speed settings for the two electric motors (decoiler and feeder) that actuate decoiled steel plate through a prototype punching press work-cell [6]. The simulation has enabled:

- performance review of the existing prototype;
- a reduction in the set-up time for new products; and,
- replacement of the previous trial-and-error approach used to set work-cell operating speeds with a predictive model.

This paper will report on the design process and associated outcomes, including the product and production recommendations for the press work-cell prototype investigated [7]. The work offers a case study for the performance of mechatronic system design in an industrial environment [8]. The case study has, as its focus, the impediments associated with the integration of highly evolved mechanical systems and poor control system architecture.

2. Background

A novel punching press work-cell has been developed (figure 1). It incorporates many innovative features that are based around continuous production using coiled metal. The punching system within the overall work-cell has such a high productivity that problems associated with material handling became apparent, especially within the "product handling" system.

Conceptual engineering design techniques were used at all stages of the investigation [8]. An extensive review of the performance of the existing prototype was completed to gather the necessary understanding when applying evaluation techniques to the alternative design concepts.

Initially, the manual product handling system was considered most in need of redesign where an automated or even semi-automated stacking system was considered vital for improved productivity. A design review of the prototype identified that the work-cell prototype also had a material handling productivity deficit at the input side, where continuous metal plate (raw material) is automatically fed into the punching system. Regular stoppages were observed due to limitations of the material flow controller at the input to punching. These stoppages diminished when material flow rate was decreasing, with an associated detrimental effect on work-cell productivity. The participants in the collaborative project agreed that all systems should be investigated more fully to gain a better understanding of deficits in the prototype work-cell.

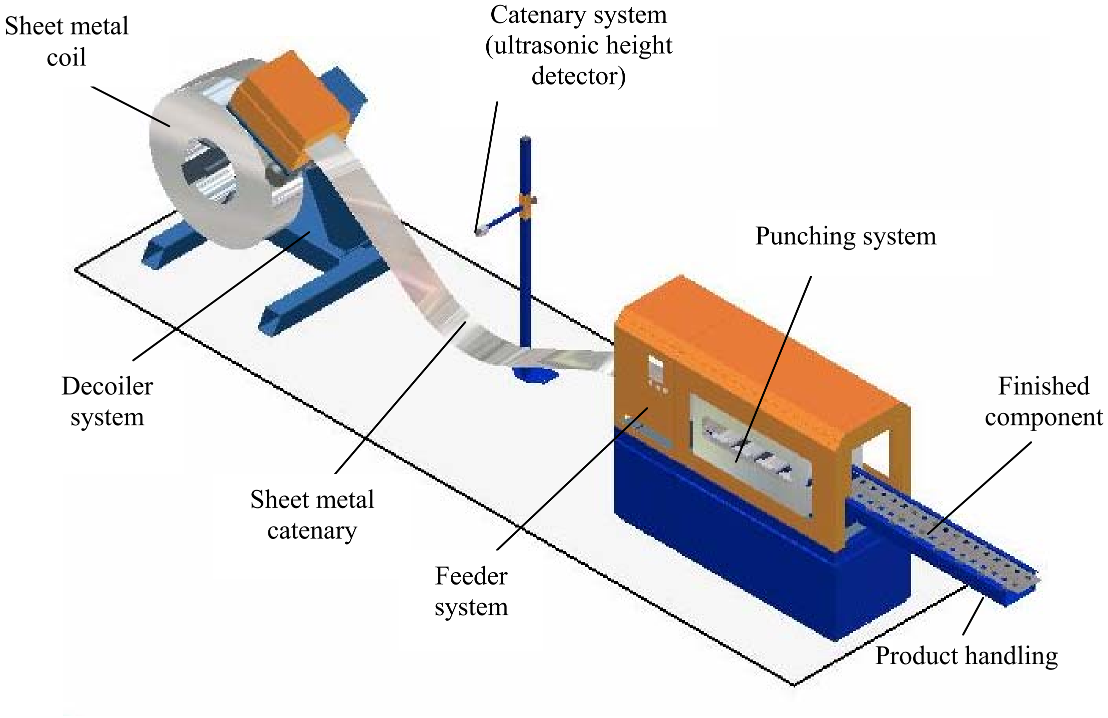


Figure 1: Layout of prototype punching work-cell, identifying associated systems.

The work-cell was decomposed into functional systems [9] to provide a functional analysis of the overall design and to better understand the synergy between mechanical, power electrical, electronic and computer control [10]. The synergy investigation resulted in the identification of three alternatives to improve work-cell performance:

1. replace the decoiler electrical motor, controlled by an inverter drive, with a servomotor;
2. develop and implement an improved control architecture for the catenary system;
3. develop an off-line simulation of the work-cell to better understand the behaviour of the catenary system when work-cell systems parameters are changed.

The merits associated with these alternatives were evaluated against an agreed performance criteria set and a series of associated constraints that were specified by the collaborating company:

- minimise cost;
- minimise duration to implement (i.e. disruption to normal operation);
- minimal difficulty of implementation (i.e. not requiring significant expertise not available within the collaborating company).

A comparison table was used to evaluate the three solution proposals, with the off-line simulation chosen (table 1). The off-line simulation had a low projected cost, with minimal associated infrastructure. Electric motor replacement with a servomotor was considered to be the most expensive proposal due to both hardware (motor and associated control panel) and technical commissioning costs. The collaborating company engaged a third-party to install the existing control architecture. Direct access to the existing control software was not available. The project team did not have the necessary expertise to write, install and test a new control system without taking the work-cell off line for a significant period. The company could not absorb the associated delays to contracted production.

The off-line simulation offered minimal disruption to normal operation except during the test phase when adjustment of available control parameters could be completed to evaluate the accuracy of the simulation against the working prototype. Implementing the off-line simulation would be readily accomplished, apart from fine-tuning the simulation to best model performance changes of the prototype when control parameters are adjusted.

Table 1: Comparison table of the different solutions proposed.

	Weighting	**Servomotor**	**Control architecture**	**Off-line simulation**
Projected Cost	*10*	5	7	10
Duration of implementation	*6*	7	6	8
Difficulty of implementation	*8*	7	5	8
Weighted Total		**148**	**147**	**212**

0-2: Inadequate solution 3-5: Poor to satisfactory solution 6-8: Good to very good solution 9-10: Excellent/ideal solution

3. Simulation design – an introduction

The off-line time-motion model, or "simulation", was developed to simulate the movement of continuous metal plate fed through the work-cell's automated systems: decoiler, loop, feeder and punching. The product handling involves finished punched-plate components being moved from the work-cell conveyor onto pallets for dispatch (figure 1). This final system is fully manual in the existing prototype work-cell and was not included in the simulation. The simulation has been used to analyze and evaluate the dynamic performance of the automated systems within the prototype and offers new strategies for subsequent punching work-cell designs.

Preliminary performance studies of the existing work-cell showed the decoiler and catenary systems to be the least efficient. This was obvious through visual inspection so accurate time trials were not required. For example, the catenary quickly reached its maximum or minimum available levels, resulting in a machine interrupt (i.e. shut-down), every time material flow rate was increased beyond a level that could be accommodated. This saturation rate would vary with product specification (i.e. punching sequence). A more detailed modelling was completed on the decoiler and catenary systems than for the far more efficient feeder and punching systems.

The simulation was designed to enable off-line experiments to be performed rapidly and inexpensively [14] and was used to demonstrate the consequences of alternative operating strategies. Operator safety was not compromised as the consequences of extreme settings were assessed off-line.

4. Simulation design – from concept to implementation

Tasks completed in the design and development program for the work-cell, prior to integration into the production environment [7]:

Catenary and decoiler systems: complete experiments to gain performance data from the existing prototype; determine relationship between catenary position and feed distance; and, relationship between catenary position and decoiler linear speed.

Feeder system: determine decoiled plate linear speed at the feeder; estimate the acceleration and deceleration times and feed distances within a feed cycle; determine feed distance under feeder motor saturation speed.

Punching system: review servo-hydraulic feedback control for the physical punching system; detailed review of the punching system signals; model a complete punching cycle.

The objectives of the simulation design were:

- predict the behaviour of material flow over a range of (motor) feed settings;
- check the disrupt ratio of the system, which corresponds to the sheet metal catenary moving outside an accepted operational zone (maximum and minimum catenary heights);
- predict production capacity when the model is provided with specific operating settings;
- seek to find the best, if not the optimal, speed setting against specified operating performance criteria, in order to improve overall efficiency of the work-cell prototype [10,11].

4.1 Simulation development

A principle objective of the simulation was to represent the catenary behaviour of the prototype, which has been identified as one of the least efficient systems. Figure 2 shows the area that has been simulated.

The simulation has the following input parameters:

- Punching sequence;
- Maximum speed of the feeder;
- Minimun and maximum speed of the decoiler.

The punching sequence is dictated by the product that is been produced. No changes can be made to alter the punching sequence in order to alter the behaviour of the catenary. Therefore, the only parameters that can be changed are the feeder and decoiler speeds. These parameters play a major role in how the catenary behaves, and consequently, on overall work-cell efficiency.

4.2 Simulation algorithm

The simulator produced is based on the flow chart algorithms shown in figures 4 and 5. The iterations presented in these flow charts (n = 50 and n = 20, respectively, were selected following an exhaustive review of work-cell performance and observed product variation. The associated equations were developed empirically, based on available information from the existing prototype. Figure 4 shows a summary of the model developed for the movement of metal plate within the decoiler, loop, feeder and punching systems.

Relationship found for catenary position and feed distance:

$$y'_c = -5E\text{-}06\, x^3 + 0.0015\, x^2 + 0.9293\, x + 0.3755 \qquad \text{(Eq. 1)}$$

The decoiler linear speed is calculated using:

$$v_d = \pi\, d\, n_m / 60\, i_d \qquad \text{(Eq. 2)}$$

where: diameter of the feeder system pinch rollers, d_r = 60 mm
rate of rotations of the decoiler electric motor, n_m
gear reduction, i_d = 11.83

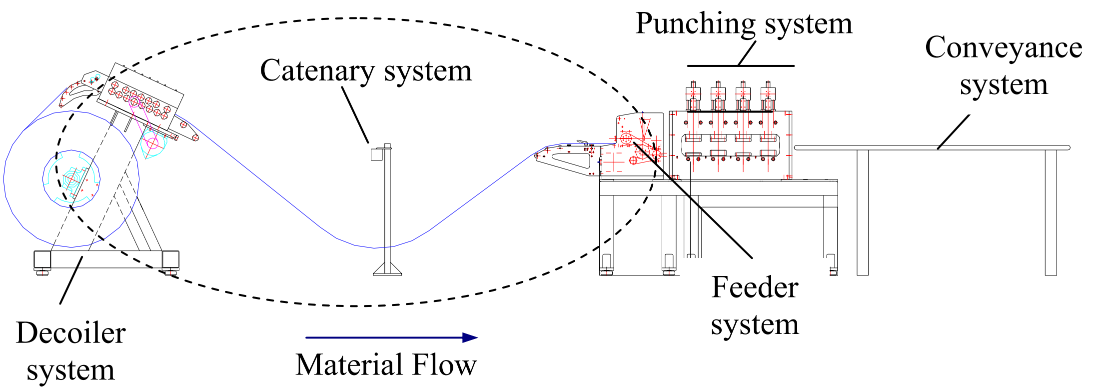


Figure 2: Schematic elevation view of a punching work-cell, showing the area of greatest interest for the time motion simulation.

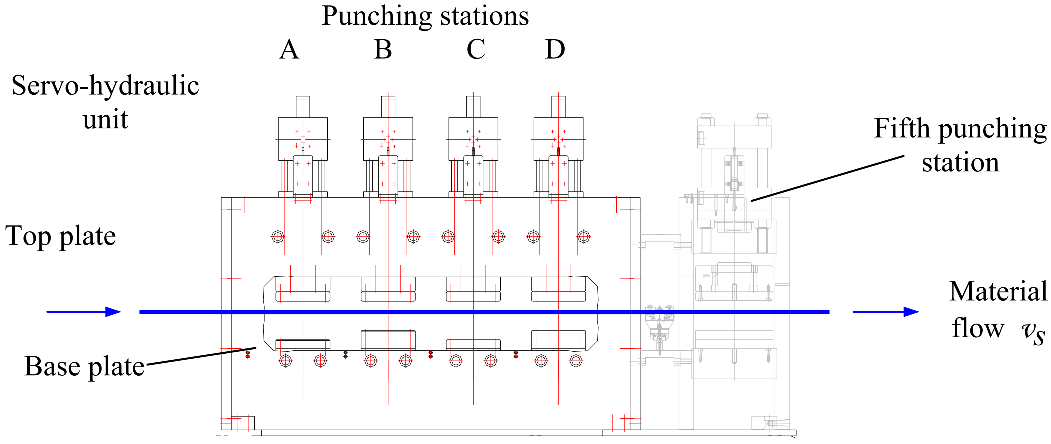


Figure 3: Schematic drawing of the punching system with a series of servo-hydraulic punching stations.

Relationship between catenary position (y'_c) and decoiler linear speed (v_d):

$$v_d = (-0.000044\, y'_c)^{2} + (0.0093\, f_{max} - 0.0093\, f_{min} - 0.00004)\, y'_c + (0.0869\, f_{max} + 7.449\, f_{min} + 0.1443) \qquad \text{(Eq. 3)}$$

where: f_{max} = upper level frequency (Hz)

f_{min} = bottom level frequency (Hz)

y'_c = sheet metal catenary position (mm).

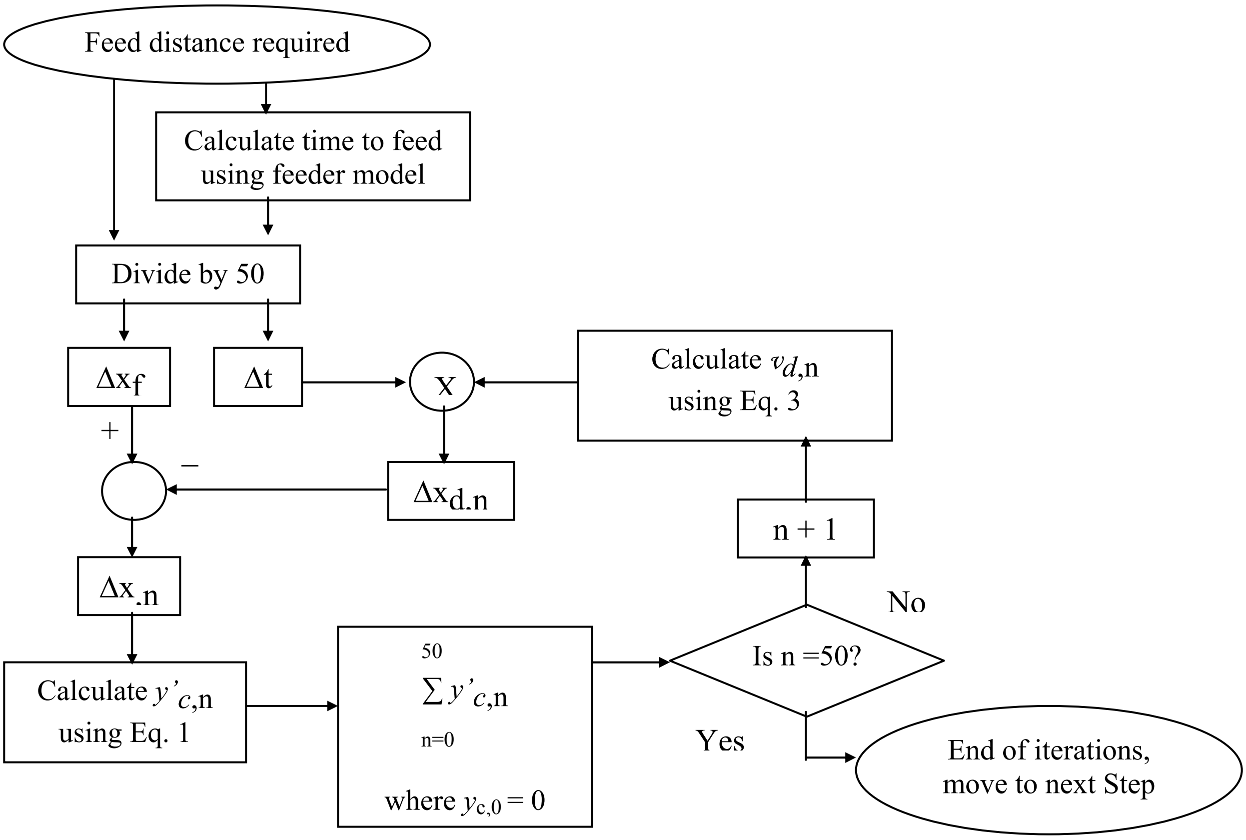


Figure 4: Algorithm flow chart for feed distance time increments.

Equation 2 enables the calculation of the decoiler linear speed (v_d) as a function of the lower (f_{min}) and upper (f_{max}) frequency levels, which correspond to decoiler speed of operation (i.e. $w_{d,min}$ and $w_{d,max}$ respectively).

For each new punching sequence, the *percentage of synchronous speed* (PSS) has to be entered in the work-cell human machine interface (HMI). This input limits the maximum angular speed of the feeder system servomotor to the PSS chosen.

Figure 5 shows the time-motion algorithm for the work-cell simulation. Two approaches were trailed when developing the modelling algorithm (figure 6): assume a quadratic acceleration and deceleration phase with a linear intermediate (approach #1); and, ignore the acceleration and deceleration quadratic phase and just presumes a linear feed distance (approach #2). Preliminary trials of both approaches were compared with output data from the prototype work-cell, with approach #2 showing a better correlation than approach #1. The reason for this is unclear and will be the subject of additional studies. For now, the approach with he best correlation to observed performance (approach #2) is used in the simulation.

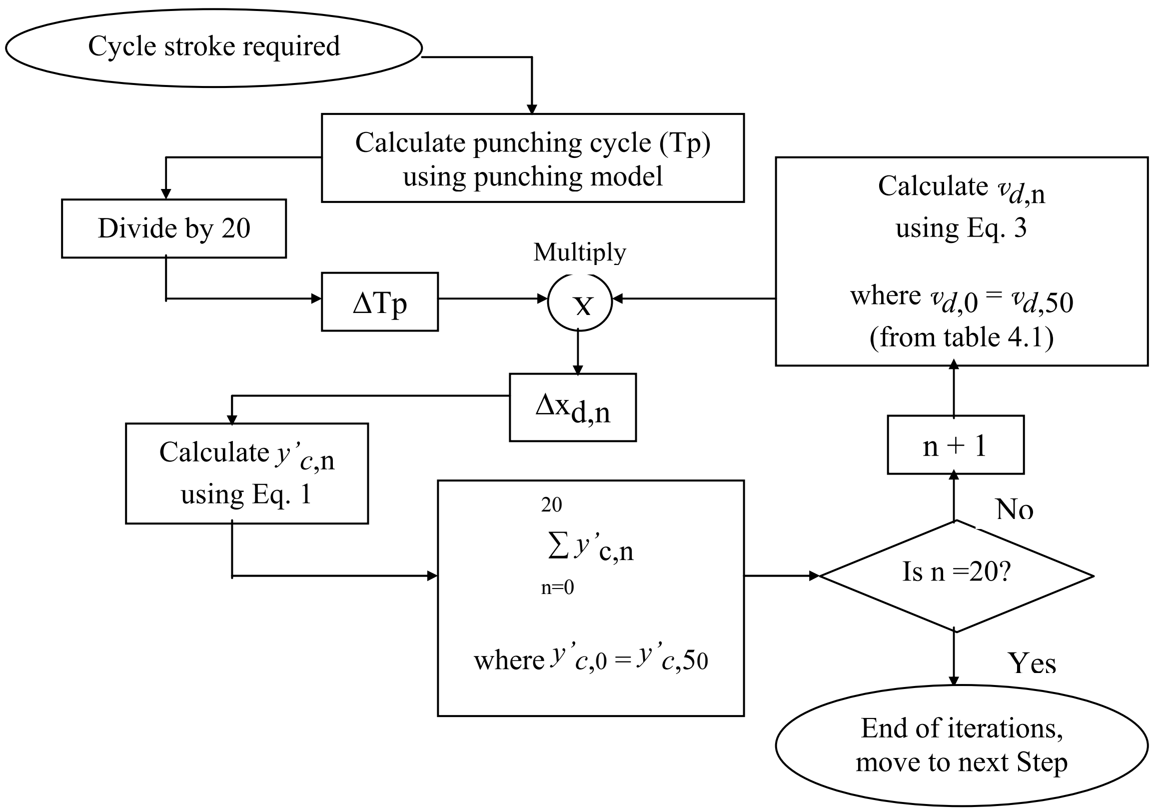


Figure 5: Algorithm flow chart for punching cycle time increments.

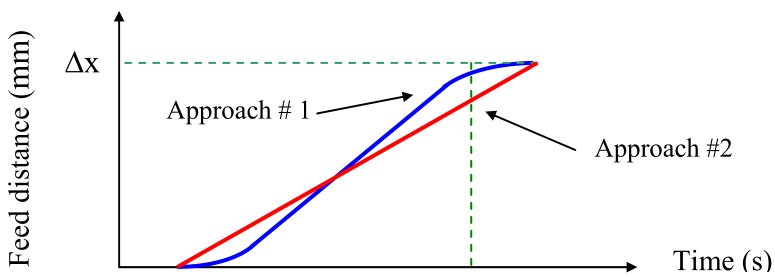


Figure 6: Incremental metal plate feed simplifications.

4.3 Punching sequence case study

The existing work-cell had been in commercial production for 24 months prior to the commencement of the collaborative project. In this time, a trend of product types became apparent. This section explores a punching sequence that includes many of the features commonly found through commercial precedent. The company collaborator uses the designation PWP236 for this sequence (figure 7):

Step-1: feed 585.5 mm
(historically, 85% of feeds are no greater than 150 mm)
Step-2: punch A (figure 3), stroke = 3 mm
(historically, 83% of the punch cycle strokes are between 3 mm and 7 mm)
Step-3: feed 658.5 mm
Step-4: punch
D, stroke = 7.5 mm
Step-5: feed 3 mm
Step-6: punch D, stroke = 7.5mm

Using this punching sequence, the original 'trial and error' approach adopted by the company to set the available HMI parameters resulted in:

- maximum feeder speed (PSS = 9%); and,
- minimum and maximum decoiler speed (f_{min} = 25 Hz and f_{max} = 80 Hz).

The step-1 feed process was modelled to estimate the duration of the feed using the linear feed simplification – approach #1 (figure 6). The model estimates a feed time of 1.5 sec. As this length of metal plate is being fed, the sheet metal catenary (y'_c) rises, and consequently, the decoiler motor responds to this change in y'_c, adjusting its speed within the HMI inverter frequency setting range. The variation in y'_c is dependent on the difference between the material flow at the decoiler and the material flow at the feeder at each incremental time.

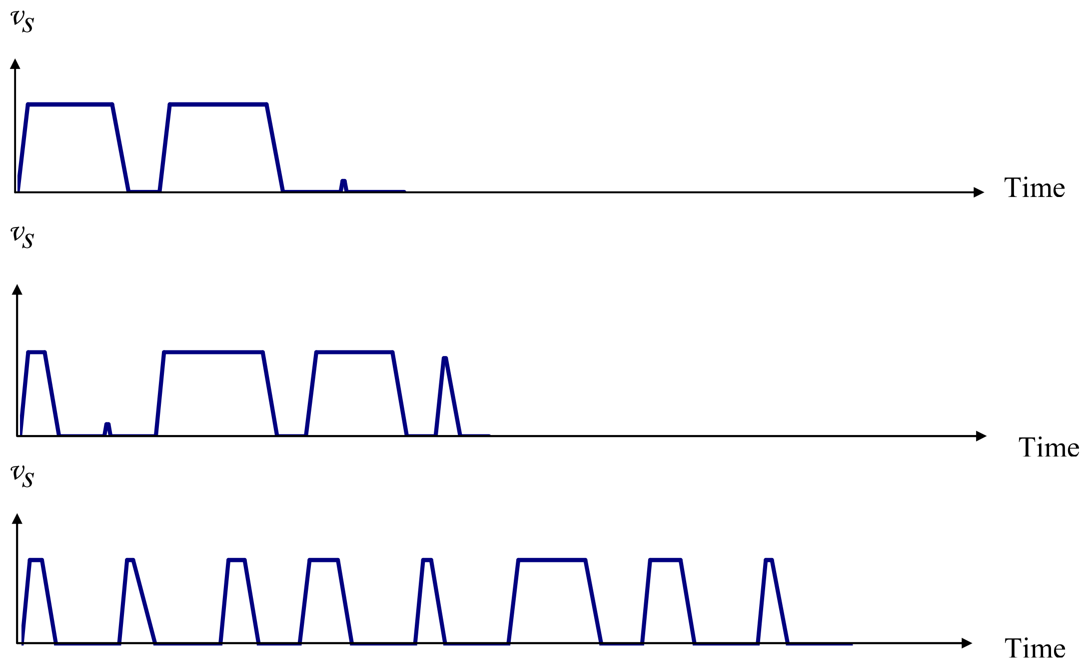
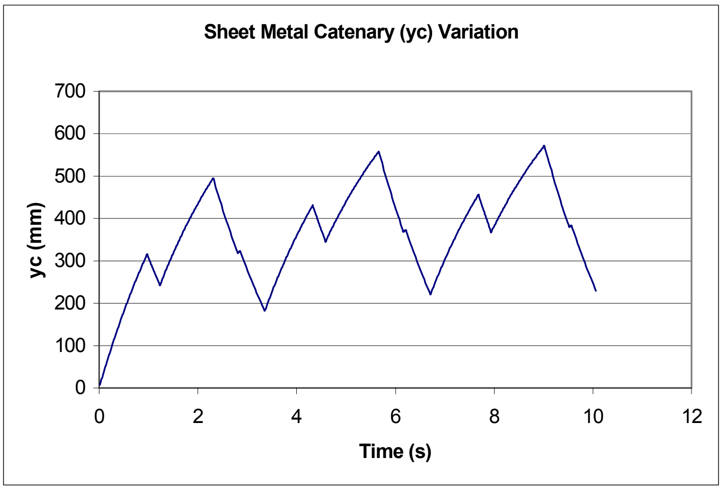


Figure 7: Common product sequences used in the work-cell prototype. Top: designation PWP236 (case study sequence in section 4.3). Middle: designation EP236. Bottom: designation BBuddy.
A common time domain is used for each of the sequences.
v_s = decoiled metal plate velocity.

At the completion of step-1 (x = 585.5mm), the final results obtained from the feed distance algorithm (figure 4) are: final y'_c position = 214 mm and final decoiler motor speed, v_d = 301 mm/s (w_d = 1140 rpm).

Step-2 is a punching operation with punch A having a cycle stroke of 3 mm. During this step, the feeder is not supplying any metal plate, but the decoiler system is able to continue supplying metal plate, stopping when the catenary geometry reaches y'_c = 0 (i.e. when the catenary is closest to the floor).

Calculating Δx, y'_c, and v_d is completed using the algorithm shown in figure 5. At the completion of step-2 (punch A, stroke = 3 mm), the final results obtained from the punching cycle time algorithm (figure 5) are: final y'_c position = 152.6 mm and final decoiler speed, v_d = 270 mm/s (w_d = 1024 rpm).



Feed Distance (mm)	Time to Feed (s)
585.5	1.49

Figure 8: Feeder system speed profile for case study step-1 with a PSS of 9%.

This procedure is followed for each Step in a punching sequence, in this case, step-3 to step-6. The case study punching sequence simulation produced the vertical catenary height variation represented in figure 9. For continuous production to occur, the catenary height y'_c must be the same at the start and end of the production cycle. Otherwise, an instability is introduced. Figure 10 shows a simulation of six production cycles and predicts that the catenary height variation cycle quickly achieves a repeatable behavior inside the physical limits (for the prototype work-cell, 10 and 700 mm). This matches the observed behavior of the prototype where the catenary height stabilizes in the range 70 mm $< y'_c <$ 320 mm.

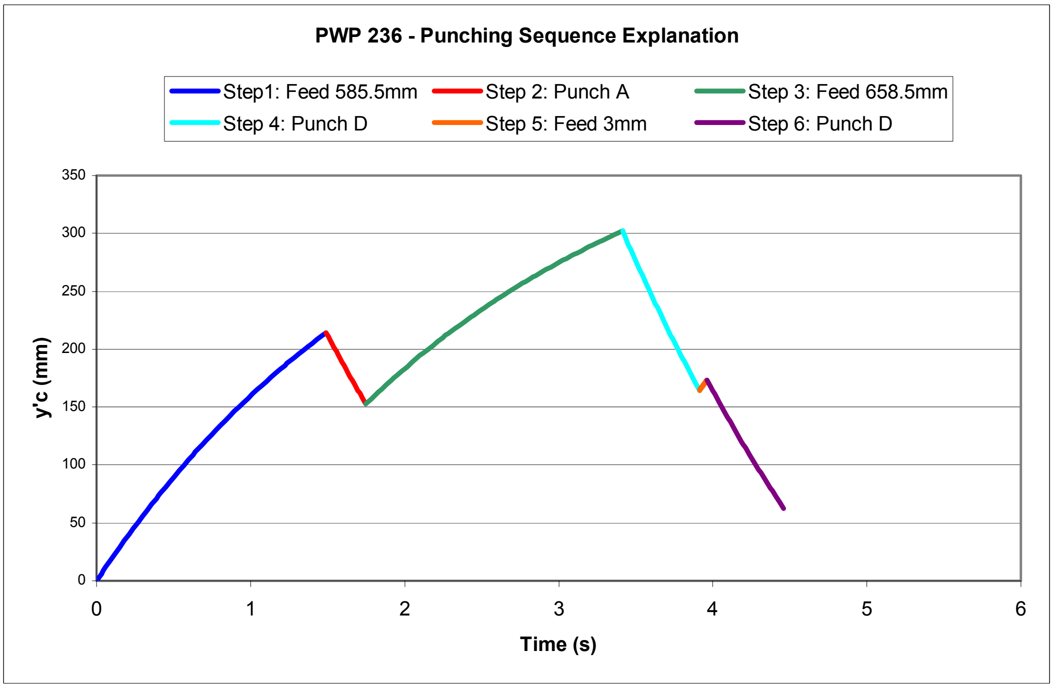


Figure 9: Punching sequence case study – catenary height variation.

Prior to this collaborative work, a 'trial and error' approach with the available HMI parameters (f_{min}, f_{max} and PSS) was completed. This normally resulted in a lowering of production rate (PSS). Using the computer based simulation, off-line experiments are completed to predict catenary behaviour prior to production. In particular, opportunities to increase PSS while maintaining catenary stability and the criterion of achieving a decoiler motor speed as constant as possible (i.e. f_{min} and f_{max} set as close as possible) are now investigated systematically.

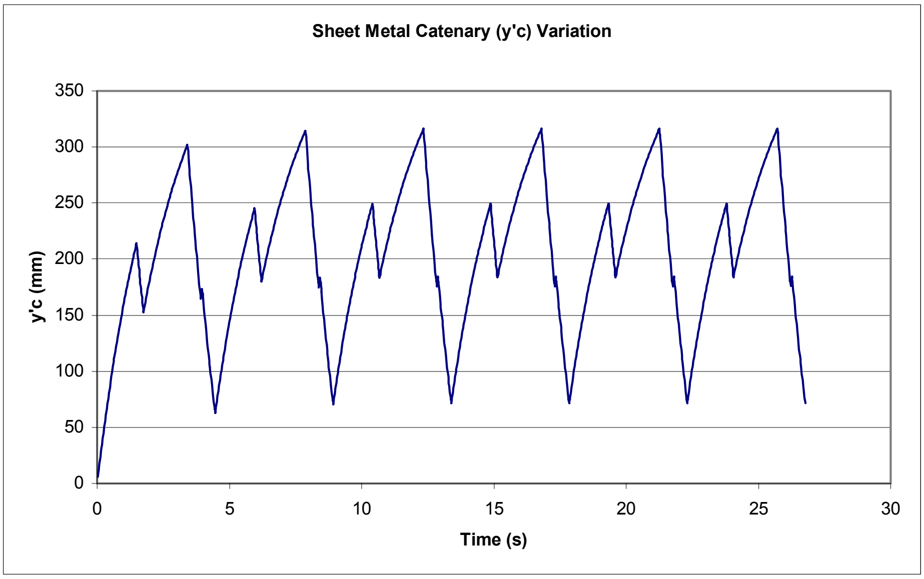


Figure 10: Continuous punching sequence (six cycles) – catenary height variation.

4.4 Comparative studies – prototype and simulation

Data acquisition was completed to compare the performance of the prototype work-cell and the computer simulation. The data stream associated with the ultrasonic sensor and decoiler motor speed were interrogated and stored.

Figure 11 shows catenary movement obtained from the data acquisition and the simulation for the case study sequence. The lowest data acquisition frequency available is 0.5 seconds per interrogation (a limitation of the work-cell hardware/software). The loss of intermediate data points is apparent, for example, obvious peaks have been truncated due to the low data retrieval frequency. The observed limitations of the time-motion simulation in this case study sequence:

- there is a variation in both the minimum and maximum catenary height ranges;
- the simulation predicts a shorter sequence cycle than that observed in the prototype – there is an increasing offset between the curves in figure 11 over multiple sequences.

Consistant observations were made during a series of trials on different product sequences [7].

The mismatch between prototype and simulation was, to a certain extent, expected due to the simplifications present in the simulation, in particular, the linear approach used to simulate acceleration and deceleration of the punching and feeder system. The high inertias associated with the decoiler system is also likely to have a significant effect on the performance of the prototype (steel coils can weigh up to 900 kg).

Experiments were completed on the work-cell prototype to determine the extent of the simulation error. The three most common production components were used (figure 7 outlines the sequences for each). Product variation is mostly associated with the number of steps (punching operations) required in a production cycle. Inertia factors were introduced to the simulation so as to better match the observed catenary behavior – decoiler (I_d) and feeder and punching system (I_{fp}). The prototype inertia factors observed for the three production components were I_{fp} = 5% and I_d = 11%.

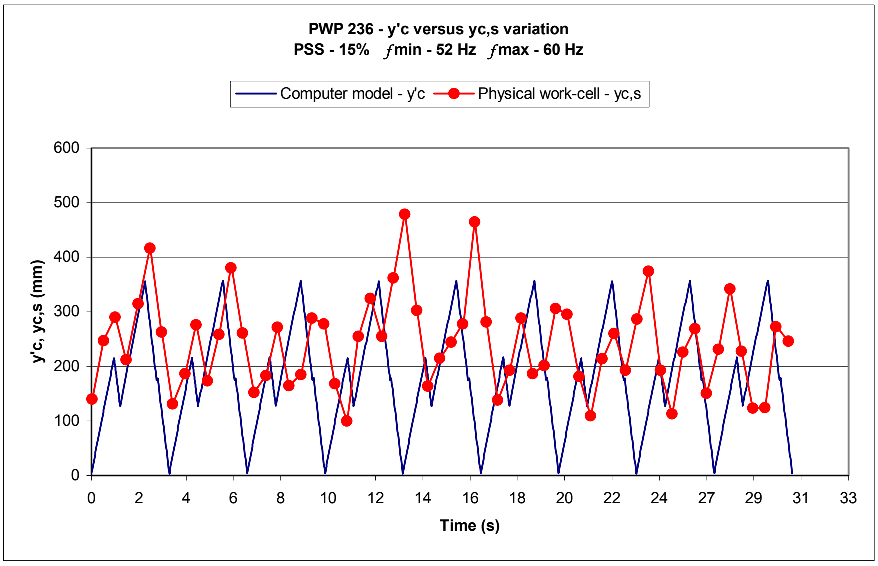


Figure 11: Catenary movement variation for case study product
Blue trace: simulation y'_c, Red trace: prototype work-cell $y_{c,s}$.

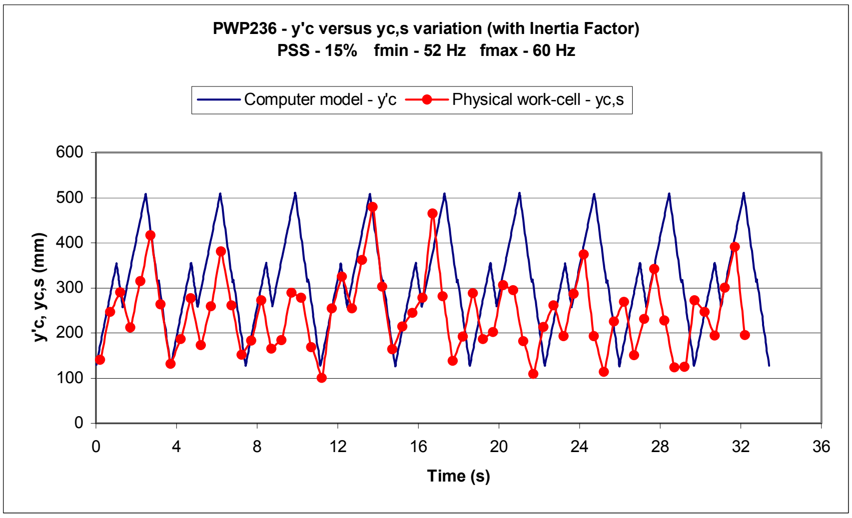


Figure 12: Catenary movement variation for case study product with intertia factor applied to the simulation
Blue trace: simulation y'_c, Red trace: prototype work-cell $y_{c,s}$.

Figure 12 shows catenary height variation for the case study product (PWP236) with the inertia factors applied to the simulation. The catenary height stabilized within the range 130 mm < y'_c < 500 mm, offering a more precise match than the simulation without an inertia factor (figure 11). The introduction of the inertia factor improved the catenary height variation simulation for production components with a larger number of punching steps within a sequence (e.g. BBuddy, figure 7 Bottom, production sequences shown in figures 13 and 14). The inertia factor had a significant impact on the predicted stabilization height of the catenary, with an improved accuracy of prediction for work-cell catenary height range.

The simulation did not offer any substantial change to catenary height prediction for product sequences with an intermediate number of steps within a production sequence with the introduction of inertia factors (e.g. EP236, figure 7 Middle). This finding will be the subject of future research, and is outside the scope of this paper.

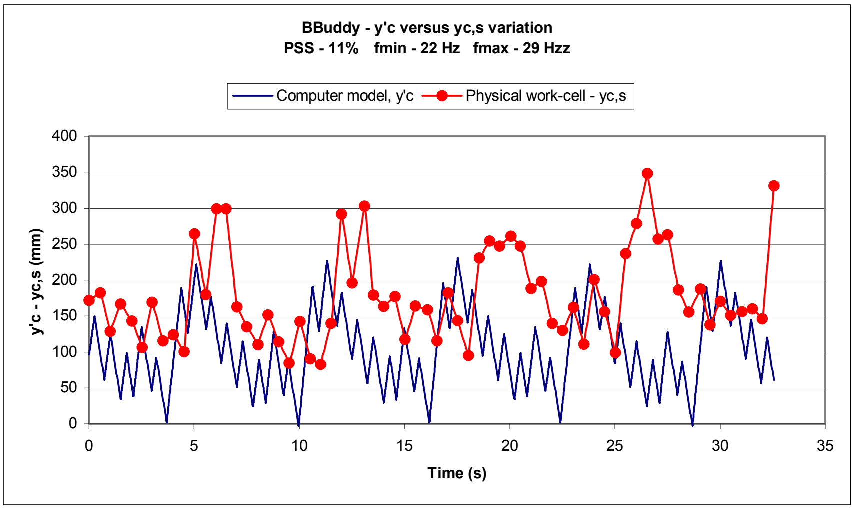


Figure 13: Catenary movement variation for products with a larger number of punching steps (figure 7, Bottom)
Blue trace: simulation y'_c, Red trace: prototype work-cell $y_{c,s}$.

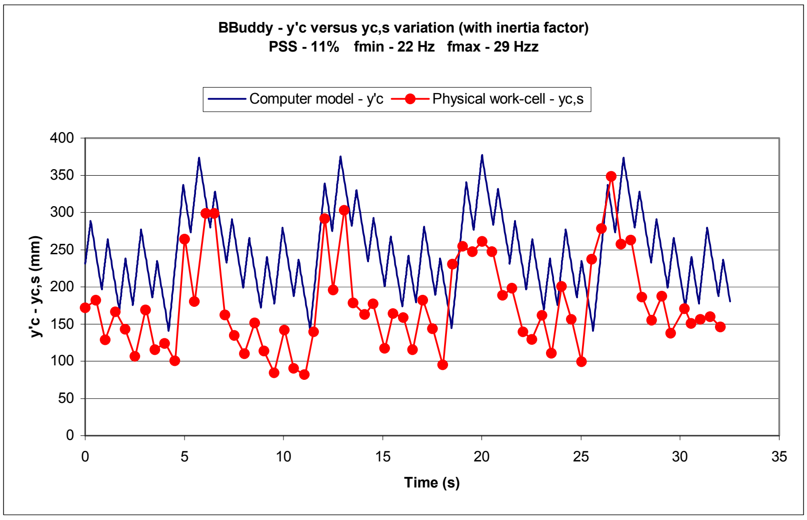


Figure 14: Catenary movement variation for products with a larger number of punching steps
with inertia factor applied to the simulation (figure 7, Bottom)
Blue trace: simulation y'_c, Red trace: prototype work-cell $y_{c,s}$.

Table 2 summarises comparative studies completed on the three production components (i.e. PWP236, EP2362 and BBuddy). The work-cell completed ten trials for each of the components. Each trial consisted of a production run of 10 components. The productivity predictions of the simulation were compared to the work-cell production run durations.

When there are minimal punching operations in a component sequence (with a minimum of associated feed interruptions), introducing the inertia factors for the feeder and punching systems was found to actually increase the simulation's component production cycle time error. This is likely due to the overall reduction of feed acceleration and deceleration within a production cycle. For the allied case study component (PWP23), catenary height simulation error is lower with the inertia factors than without them. For smooth operation of the work-cell, the prediction of catenary height range is more critical than cycle time, in order to avoid catenary height approaching system failure levels and to minimise decoiler velocity changes (this is due to the decoiler motor wear associated with accelerating the large coil inertia).

As the number of punching operations within a component sequence increases, the introduction of the inertia factors decreases the simulation cycle time error, as more time in a production cycle is spent in the acceleration and deceleration phases.

The computer simulation was not written to precisely replicate the observed performance of all work-cell parameters, but rather, to identify opportunities to enhance the process by which enhanced and stable work-cell performance could be achieved using the available HMI parameters (f_{min}, f_{max} and PSS).

Attempting to optimize the available settings and the associated prototype performance were considered but not pursued, due to the limitations of the existing prototype control algorithm, installed by a third party contractor and not available to the participants of this work. Subsequent work-cell designs are recommended to incorporate a new control algorithm that better matches the mechanical systems. In the existing prototype, the decoiler system reacts to other systems in the work-cell. This reactive approach was chosen by the third party programmers of the existing catenary control system. The reactive behaviour of the decoiler is exacerbated by punching sequences that require a large variation in decoiler motor speed, because speed variation has an associated lag due to the high inertia of the coil and spindle. In outline, it is proposed that this reactive control architecture is changed so as to be less reactive, or even proactive, where constant decoiler speed is an optimal control outcome.

For feed distances below 150 mm, the maximum available PSS is 20%. Low values of PSS are used to compensate for the existing decoiler system. The optimal region for the current servomotor to operate efficiently is when PSS is set between 40% and 70%. For the existing prototype, 40% and 70% correspond to feed distances between 600 and 1600 mm, respectively – outside of the normal range of feed distances required by the work-cell on existing commercial products. An increase in the speed reduction between the existing servomotor and feeder rollers would enable the servomotor to operate within its efficient speed region more often.

5. Conclusions

An extensive review of the available scientific literature identified few virtual manufacturing case studies associated with the application of virtual techniques to specific manufacturing functions, such as metal punching. This paper has presented some of the tasks completed to produce a functioning virtual manufacturing simulation for an existing punching work-cell.

A detailed design review of the existing work-cell prototype, completed by the authors, revealed severe shortcomings in the design of the control system (completed by third-party contractors). While the mechanical design of the punching system, in particular, offered highly competitive productivity when compared to other metal punching machines, this productivity advantage was diminished by poor software and control design. Suggested enhancements have been made to the collaborating company for a second-generation prototype, now under development.

An off-line simulation was developed to provide the work-cell operator with a means of using the available control settings to ensure that the two actuating motors (decoiler and feeder) are as synchronised as possible (without an existing coordinating control architecture) while maximising productivity in the punching system. As the third-party system control architecture could not be accessed or modified, the work-cell could not be optimised.

However, using the off-line simulation, substantial improvements, against the required design evaluation criteria, have been achieved:

- A 40% productivity improvement in the existing work-cell prototype.
- Removed the prior trial-and-error approach used to achieve equilibrium between the two motors. The prior approach could achieve correct system operation but lacked elegance:
  Example 1: the catenary height could undergo significant height variation with associated strain on the decoiler actuation components.
  Example 2: the high torque decoiler motor could be required to accommodate highly varying speed that would be better accommodated by the low torque feeder motor that was designed to accommodate highly varying speed.
- A highly constant decoiler motor speed (required due to the high inertias associated with the steel coil being rotated).

Table 2: Comparative study of production cycle times for three production components.
Production times are the average of ten production trials.

Component	**HMI setting** F_{min}, f_{max} - PSS	**Average production time (sec) for 10 components**		
		Simulation	Prototype work-cell	difference
PWP236	25,80Hz - 9%	41.20	44.61	-7.64 %
	52,60Hz – 15% (no inertia factor)	33.54	33.03	1.54 %
	52,60Hz - 15% (with inertia factor)	37.10		12.32 %
EP236	15,90Hz – 13% (no inertia factor)	40.67	44.02	-7.61 %
	15,90Hz - 13% (with inertia factor)	42.70		-3.00 %
BBuddy	22,29Hz – 11% (no inertia factor)	62.95	69.51	-9.44 %
	22,29Hz - 11% (with inertia factor)	71.34		2.63 %

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