JCP Online First, published on January 21, 2016 as 10.1136/jclinpath-2015-203349

Predicting turnaround time reductions of the diagnostic track in the histopathology laboratory using mathematical modelling

A G Leeftink,[1,2] R J Boucherie,[1] E W Hans,[1] M A M Verdaasdonk,[3] I M H Vliegen,[1] P J van Diest[3]

▸ Additional material is published online only. To view please visit the journal online (http://dx.doi.org/10.1136/jclinpath-2015-203349).

[1]Centre for Healthcare Operations Improvement & Research (CHOIR), University of Twente, Enschede, The Netherlands
[2]UMC Utrecht Cancer Center, University Medical Center Utrecht, Utrecht, The Netherlands
[3]Department of Pathology, University Medical Center Utrecht, Utrecht, The Netherlands

Correspondence to
Anne G Leeftink, Centre for Healthcare Operations Improvement & Research, University of Twente, P. O. Box 217, Enschede 7500 AE, The Netherlands; a.g.leeftink@utwente.nl

Received 21 August 2015
Revised 11 December 2015
Accepted 23 December 2015

ABSTRACT

Background Pathology departments face a growing volume of more and more complex testing in an era where healthcare costs tend to explode and short turnaround times (TATs) are expected. In contrast, the histopathology workforce tends to shrink, so histopathology employees experience high workload during their shifts. This points to the need for efficient planning of activities in the histopathology laboratory, to ensure an equal division of workload and low TATs, at minimum costs.

Methods The histopathology laboratory of a large academic hospital in The Netherlands was analysed using mathematical modelling. Data were collected from the Laboratory Management System to determine laboratory TATs and workload performance during regular working hours. A mixed integer linear programme (MILP) was developed to model the histopathology processes and to measure the expected performance of possible interventions in terms of TATs and spread of workload.

Results The MILP model predicted that tissue processing at specific moments during the day, combined with earlier starting shifts, can result in up to 25% decrease of TATs, and a more equally spread workload over the day.

Conclusions Mathematical modelling can help to optimally organise the workload in the histopathology laboratory by predicting the performance of possible interventions before actual implementation. The interventions that were predicted by the model to have the highest performance have been implemented in the histopathology laboratory of University Medical Center Utrecht. Further research should be executed to collect empirical evidence and evaluate the actual impact on TAT, quality of work and employee stress levels.

INTRODUCTION

Due to varying reasons such as the ageing population and the growing awareness of the importance of histopathology for diagnosing disease and assessment of prognosis and therapeutic options, the histopathology laboratory nowadays experiences a growing volume of more and more complex testing.[1] Further, there is an increasing demand for short turnaround times (TATs). At the same time, healthcare costs need to be controlled, and the histopathology workforce is shrinking in many countries.[1] Despite emerging technology that has facilitated more automation, the histopathology laboratory still operates a sequence of labour-intensive, often manual, processes.[1–3] Therefore, histopathology resources and employees should be deployed as effectively as possible.[4] Moreover, reducing TATs in histopathology laboratories is challenging since it is affected by employee workload, the batch-wise way of working and workflow scheduling.[1 5]

A balanced distribution of workload is important for employee well-being and efficiency in the laboratory. Workload is measured by the amount of work and time pressure. In high-workload situations, employees have to put in much effort to complete all their tasks within certain time limits.[6] A high workload has several detrimental effects for both the employee as well as the organisation, such as fatigue, psychological distress, increased absenteeism and reduced quality of work.[7] Furthermore, high-workload situations need to be followed by longer periods of employee recovery compared with regular working and recovery situations.[8] Therefore, it is important to limit the time employees have to perform tasks in a high-workload environment. Hence, the laboratories should strive for a balanced division of workload over the day.

The TAT is a widely used quality measure in pathology, and is often used as the main performance indicator of the histopathology laboratory, together with quality indicators such as diagnostic accuracy.[9] Referring clinicians and their patients should be provided with a timely diagnosis, and same-day reporting becomes more important.[10] Therefore, results should be available as early as technically possible.[11] Studies on TAT have shown that several factors impact TAT, such as use of immunohistochemistry, the number of slides studied, diagnosis of malignancy,[9] institutional size, integration of pathology trainees, delayed slide delivery, greater specimen volume and the amount of support staff.[12] Furthermore, several technically required activities, such as fixation, decalcification and degreasing, increase TAT in the histopathology laboratory.[11]

In many hospitals in The Netherlands, tissue processing is still done overnight, due to the long processing times of the larger tissue samples that are part of a batch in the conventional tissue processors. This leads to a one-night delay. Pathologists and histotechnicians adapt their schedules to this overnight tissue processing.[2] This leads unavoidably to unnecessarily high TATs. The implications for the diagnostic workload in the histopathology laboratory are a high-workload environment in the morning and low-workload in the afternoon.[4] This requires longer employee recovery times, and comes with the aforementioned detrimental effects.[7 8]

To cite: Leeftink AG, Boucherie RJ, Hans EW, *et al*. *J Clin Pathol* Published Online First: [*please include* Day Month Year] doi:10.1136/jclinpath-2015-203349

In the present study, we applied mathematical techniques, also known as operations research methods, to optimise the process flow in the histopathology laboratory. These methods allow for prospective evaluation of organisation interventions. Currently, prospective analyses of interventions are uncommon in healthcare, since most interventions are proven through trial and error.[13 14] Quantitative support may be offered through operations research methods. These mathematical techniques offer the possibility to analyse a system without physically interfering with the system.[15] The initial way of working in our study is compared with multiple alternative approaches using a decomposed planning method based on mixed integer linear programme (MILP). A decomposed planning model consists of two or more subsequent planning phases wherein different objectives can be strived for, for example workload as well as TAT. MILP is an operations research tool for mathematical optimisation with an objective and restrictions formulated as linear functions. It has often been applied in chemical and semiconductor industries, where large batching machines are part of a larger process chain.[16] Such systems are comparable to the histopathology laboratory, where large tissue processors are in the middle of a series of processes.

The advantage of the MILP model is the ability of taking into account specific restrictions that come with the specialised activities in the histopathology laboratory. For example, pre-emption restrictions can be included, which forbid that a resident grosses tissue from two different patients at the same time, since tissue contamination should be prevented. Other examples are assignment restrictions, wherein some specimens need specific resources or specific staff members. For example, hospitals might decide that large specimens need to be grossed by residents or pathologists instead of technicians, which can be taken into account in the proposed MILP model. The MILP model, once developed, can also easily be extended to histopathology laboratories of other hospitals, by adjusting the restrictions or parameter settings.

We set out to analyse the processes in the histopathology laboratory, and possible interventions were prospectively assessed using a decomposed model with MILP, to facilitate better decision making on workflow management, resource usage and TAT, against no additional costs. The model was decomposed to assess both workload and TAT. Furthermore, we showed how TAT and workload can be used as effective performance indicators in the histopathology laboratory. Specifically, it showed how to prospectively assess laboratory performance using operations research methods, and discusses how these methods can assist healthcare decision making. The results of this study are currently deployed for optimising the workflow in the histopathology laboratory of a large academic hospital in The Netherlands.

MATERIALS AND METHODS

Setting

The study was performed at the pathology department of University Medical Center Utrecht (UMC Utrecht), one of the largest academic hospitals in The Netherlands, with over 1000 beds. In the pathology department, diagnostics, consisting of histology, immunochemistry, molecular pathology and cytology, is provided for the whole medical centre, as well as for other pathology laboratories, surrounding general practitioners and private clinics. In the histopathology laboratory, tissues of over 30 000 patients are evaluated each year.

Workflow

Specimens that arrive at the histopathology laboratory go through the predefined sequence of activities, as shown in figure 1. In the UMC Utrecht histopathology laboratory in 2013, 69% of the FTE (Full Time Equivalent) was spent on activities directly related to diagnostics (so-called primary activities). The remainder of time was used for other activities such as educational activities, cleaning activities and inventory management activities.

Regularly, tissue processing (step 2 of figure 1) was solely done overnight. However, exceptions were made for priority specimens, which were occasionally processed during the day. This exception allowed 100% of the priority specimens that arrived before 10:00 in the laboratory to be discussed at the multidisciplinary meetings (MDM) in the afternoon of the same day.

Usually, every day three residents run the grossing process and 10 technicians assist in grossing, and perform embedding, sectioning, mounting, staining and case assembly per day. One of these technicians was dedicated to support activities, such as transportation of slides. During the day, they were supported by a team of pathologists and by secretaries. Furthermore, four tissue-processing machines were available for tissue processing.

Performance indicators

The main performance indicator considered in this study was the intradepartmental TAT (ITAT), which was the total time a specimen spends in the histopathology laboratory.[11] We defined ITAT as the number of minutes from arrival of the specimens in the laboratory to transportation of the slides to the pathologist. Furthermore, the registration TAT (RTAT) was considered, which was defined as the number of minutes from the moment of transportation until the authorisation by the pathologist. The total of ITAT and RTAT defines TAT as the total time needed for each specimen to be examined and reported from the moment of arrival in the laboratory.

Data collection

Work volumes and TAT data were derived from the hospital's Laboratory Management System. Data on shifts were derived through communication with the lab manager and histopathology staff.

To assess the initial performance, 12 months of historical data were used consisting of 22 379 specimen samples (biopsies and surgical specimens). This included all specimens accessioned during regular working hours in 2013 (1 January 2013 to 31 December 2013). Muscle biopsies, which receive many ancillary studies in the testing process, were not included in this database. Exclusion criteria consisted of specimens that were embedded during the weekend, or holidays (n=12), or specimens with a TAT of more than 1 month (>20 working days) (n=282). For 1783 specimens TAT could not be calculated, as the moment of arrival or the moment of sectioning and staining was unknown. The final cohort, as shown in figure 2 consisted thereby of 20 302 specimens, which were included in this study.

Specimens were divided into four categories:

1. *Large specimens*, such as surgical specimens, which needed long fixation and were grossed by the residents. The time required for tissue processing was 8–12 h.
2. *Average-sized specimens*, such as excisional biopsies, which can be grossed by the residents as well as the technicians. In UMC Utrecht, these specimens were often derived from external parties. The time required for tissue processing was 4 h.

Figure 1 Histopathology process flow.

3. *Small specimens*, such as biopsies, which do not need to be grossed, but only to be put into a cassette by the technician. The time required for tissue processing was 3 h.
4. *Priority specimens*, which are often small-sized specimens such as myocardial and breast biopsies. The priority specimens were handled by technicians and processed as soon as possible, preferably with a same-day diagnosis.[17] The time required for tissue processing was 2 h.

Model description

A mathematical model was developed (see online supplementary appendix I),[18–21] using an iterative approach. During the 4 months of development, pathologists, residents and technicians were involved in the design and validation of the model. For example, the categorisation of specimens, together with the corresponding process flow of each of the specimen categories, was determined in collaboration with histopathology employees, based on a combination of medical and logistical requirements.

A MILP model was designed to support the histopathology processes, as it allows to determine the starting times of the tissue processors, and schedules all specimens arriving at the pathology department during the day in the first four stages (see figure 1): grossing, tissue processing, embedding and sectioning and staining. This results in a tissue processor schedule, together with a schedule of all other activities per specimen. ITATs can be derived based on these schedules, as well as the maximum peaks in workload, whereupon different scenarios can be evaluated.

The outcomes of the model were analysed in terms of the ITAT performance and workload distribution over the day. Using χ^2 tests the differences between interventions and the initial situation were evaluated. Significant findings were assumed when the p value was <0.05.

The fifth stage (see figure 1), the examination of slides by residents and/or pathologists, was excluded from the model, since too many external factors, such as educational and research tasks, influenced the behaviour of staff in this phase and no clear examination schedule could be derived. As a result, RTAT was not included in the model.

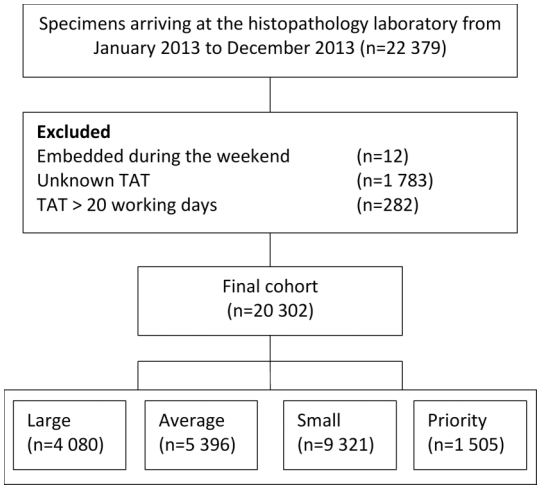

Figure 2 Flowchart of specimen inclusion. TAT, turnaround time.

The model ran on a laptop personal computer using AIMMS 4.0 mathematical modelling software,[22] with MILP solver CPLEX 12.3.[23]

Validation

To validate the model, a random selection of 10 datasets based on historical data covering one day was evaluated. Two validation methods were used:[24]

- Face validation, wherein involved pathology employees were asked whether the model reflected reality.
- Output validation, wherein the ITAT performance of the model using the aforementioned datasets was compared with the actual ITAT outcomes of the same days.

Possible interventions

Possible interventions were developed and selected in collaboration with UMC Utrecht pathology employees, during multiple group sessions. For example, in one of the meetings the employees were asked to give input on their perceived optimal laboratory opening hours and shift schedule. Using this information, multiple interventions were developed, which varied in the moment of tissue processing, and in the laboratory opening hours. Given these interventions, the model will find the best possible schedule. The designed interventions are assumed to only influence the ITAT, and not the RTAT. Therefore, if an intervention decreases the ITAT, we believe that the overall TAT will be reduced as well. The following situations were evaluated.

Baseline situation (no intervention)

In the baseline situation, tissue processing was only performed during the night, except for one batch of priority specimens. This situation corresponded with the regular way of working of the UMC Utrecht histopathology laboratory.

Intervention I: tissue processing during the day for all specimens

All histopathology employees supported the need of tissue processing during the day, to level the workload and shift the peaks from the morning towards the afternoon.

Intervention II: staggered shifting

In the initial situation, all staff assigned to a specific activity started and ended their shifts at the same time. Staggering the shifts could provide a more efficient start in the morning, where a small number of staff can perform all starting tasks, without other staff waiting for them to be able to begin their job. Furthermore, it ensures that the work can be finished in the afternoon, since the late-shift employees can finalise the cleaning in the end of the day after the other staff went home.

Intervention III: earlier opening hours

Literature showed that technicians should start embedding directly after the tissue-processing batch is finished, to minimise

the waiting time in the laboratory.[25] For the night run, the embedding shift should therefore ideally start around 04:00. In The Netherlands these opening hours cannot easily be realised for histopathology staff due to governmental regulations. However, there are opportunities to start 1 or 2 h earlier than the baseline practice.

Interventions I+II: tissue processing during the day combined with staggered shifts

It was hypothesised that more tissue processing during the day leads to more workload in the afternoon. This may increase the need for staggered shifts to ensure sufficient workforce in the afternoon. Therefore, a combination of intervention I and intervention II was evaluated.

Interventions I+III: tissue processing during the day combined with earlier opening hours

It was hypothesised that when residents start grossing earlier (the direct consequence of earlier opening hours), more tissue could be processed during the day. Therefore, a combination of intervention I and intervention III was evaluated.

RESULTS

Baseline situation

In total 20 302 specimens were included in this study, from which 4080 (20%) were large specimens, 5369 (26%) were average specimens, 9321 (46%) were small and 1505 (7%) priority specimens. The mean number of arrivals per day was 80 specimens (range: (34, 122)).

The mean observed ITAT performance was 1.67 days (σ=1.26 days), as shown in table 1. The mean observed ITAT varied between the different specimen types, as shown in table 2. Large specimens took 2.79 days (σ=1.69 days), small specimens 1.60 days (σ=1.02 days) and average specimens 1.16 days (σ=0.70 days) on average to be completed. The distribution of ITAT per specimen type is also depicted in figure 3, where every dip indicates an extra night. Figure 3 shows that the distribution of ITAT for average specimens and small specimens differs: small specimens encounter the one-night delay more often, which is shown by a higher mean ITAT.

Validation

To validate the model, output validation and face validation were applied. The output validation compared the ITAT performance of the modelled initial situation, based on a random selection of 10 datasets of historical data, to the observed ITAT performance, as shown in tables 2 and 3, respectively. This showed that the observed ITAT performance of the large, average and small specimens did not significantly differ from the modelled ITAT performance (p=0.883; p=0.139; p=0.787). However, for priority specimens there was a large and significant difference (p=0.003).

For the face validation, the model input and output were shown to pathology employees, and they agreed that the output of the model reflected reality, despite the significant difference in priority specimen performance.

Interventions

As shown in table 3, the modelled ITAT decreased by up to 24% for intervention I (p<0.01), up to 24% for interventions I+II (p<0.01) and up to 25% for interventions I+III (p<0.01). Interventions I+III seem to perform best, although ITAT performance was not significantly different from intervention I. Furthermore, the model showed no significant benefits of staggered shifting in terms of TATs compared with the baseline situation and to the situation with tissue processing during the day.

Figure 4 shows the baseline distribution of primary activities over the day, against the number of available technicians, showing that workload peaks occur in the morning, while the afternoon workload is relatively low. At multiple time points the workload in the laboratory exceeds the number of employees available. Introducing tissue processing during the day (intervention I) resulted in a more levelled workload, as shown in figure 5. Combined with earlier working hours (interventions I+III) the morning peaks reduced even more, as shown in figure 6.

DISCUSSION

The growing workload in the histopathology laboratory while the workforce is shrinking,[1] together with higher demands on TAT, necessitates efficient planning of activities to ensure an equal division of workload over the day and low TATs. Adapting an operations research approach to pathology settings resulted in valuable insights. The developed model predicted that in the UMC Utrecht up to 25% of the initial ITAT can be reduced when tissue processing during the day is implemented and workflow becomes more continuous instead of batch-driven. Furthermore, combining this with grossing small-sized and average-sized materials earlier in the morning, the workload will be more levelled throughout the day, with less peak moments in the morning.

In the observed baseline situation, small-sized specimens showed a higher TAT than average-sized specimens, despite their shorter tissue-processing time. Most of the average-sized specimens were collected from external parties and were therefore received in the end of the day (resulting in a lower ITAT) and analysed with more priority by a dedicated pathologist (resulting in a lower RTAT), which was the standard way of working in the baseline situation to ensure a rapid diagnosis for

Table 1 Observed overall TAT performance (20 302 specimens)

	Mean	(σ)	Range (min, max)
ITAT*	1.67	(1.26)	(0.14, 16.24)
RTAT†	2.10	(2.26)	(0.01, 18.00)
TAT‡	3.77	(2.75)	(0.16, 19.99)

*ITAT: Time from arrival in laboratory until transportation towards the pathologist for examination.
†RTAT: Time from transportation towards the pathologist, until authorisation of the results.
‡TAT: Time from arrival in laboratory until authorisation of the results.
ITAT, intradepartmental TAT; RTAT, registration TAT; TAT, turnaround time.

Table 2 Observed TAT performance per specimen type (20 302 specimens)

	ITAT		RTAT		*TAT*	
	Mean (σ) in days		Mean (σ) in days		Mean (σ) in days	
Large (n=4080)	2.79	(1.69)	2.88	(2.69)	5.67	(3.2)
Average (n=5396)	1.16	(0.70)	1.04	(1.34)	2.20	(1.64)
Small (n=9321)	1.60	(1.02)	2.48	(2.28)	4.07	(2.52)
Priority (n=1505)	0.99	(0.78)	1.43	(1.87)	2.43	(2.14)

ITAT, intradepartmental TAT; RTAT, registration TAT; TAT, turnaround time.

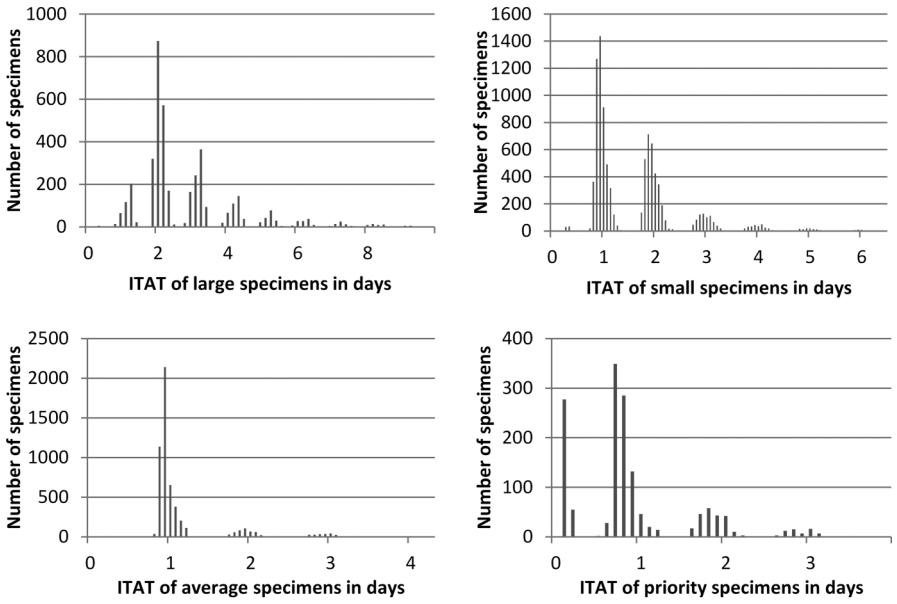

Figure 3 Observed distribution of intradepartmental turnaround time (ITAT) in days per specimen type (20 302 specimens).

these specimens. This may have resulted in prioritisation of the average- over the small-sized specimens.

Surprisingly, in the observations for the baseline situation, the priority specimens showed a high ITAT, although it is expected that these specimens are processed the same day or within 24 h. This may be due to a diagnosis registration mismatch. Pathologists do deliver the diagnosis at the MDM on time, but often do not succeed in immediately creating the report and registering the diagnosis in the computer system, resulting in a delay of a few hours or to the next morning. The validation showed a large significant difference in observed and modelled ITAT performance for priority specimens, due to this diagnosis registration mismatch. Despite this significant difference, we, together with the pathology employees, consider the model a valid representation.

We observed that the validity of the model highly depended upon the time distribution of specimen arrival. Furthermore, it also depended on the employee behaviour. For example, it was assumed that all employees work equally fast during every moment of the day and no overtime was allowed. Therefore, the model sometimes delayed the processing of tissue to the next day, while in practice employees work longer, or faster at the end of the day to ensure all tissue to be available for the tissue-processing overnight run. Another assumption made was that all batches would have approximately equal loads for the subsequent stages if divided over the day. However, if the arrival pattern of specimens through the day shows high variation, then it might happen that in the grossing stage no samples are available to process at certain times during the day, while at other moments there is a large queue. By including different release time patterns of specimens to the batching problem, the impact of variation can be analysed and robust solutions can be found. However, including arrival patterns in the model will require intensive computing power.

Due to modelling restrictions of complex human behaviour, the RTAT was not included in the decomposed planning model. However, even though we assumed the interventions only to impact the ITAT, the interventions may have impact on the RTAT as well, and therefore increasing or decreasing the TAT. Further research should be executed to collect empirical evidence to evaluate the actual impact on TAT.

The model showed that through earlier starting grossing shifts in combination with tissue processing during the day, more tissue can be grossed before the start of tissue-processing batches, which allows for more tissue to be finished the same day. It was noticed that using the model, the small-sized

Table 3 TAT performance of the mathematical model for different sample categories

	Large specimens		Average specimens		Small specimens		Priority specimens	
	E (ITAT)*	Range†	E (ITAT)	Range	E (ITAT)	Range	E (ITAT)	Range
Initial situation	2.87	(2.00–3.91)	1.49	(1.26–1.58)	1.51	(1.27–1.68)	0.25	(0.19–0.29)
Intervention I‡	2.82	(1.94–3.10)	1.00	(0.75–1.46)	0.92	(0.73–1.59)	0.24	(0.13–0.90)
Intervention II§	2.89	(2.01–3.89)	1.54	(1.30–1.62)	1.57	(1.31–1.73)	0.29	(0.23–0.33)
Intervention III¶	2.85	(1.98–3.89)	1.52	(1.30–1.60)	1.54	(1.29–1.71)	0.25	(0.19–0.29)
Interventions I+II	2.82	(1.94–3.09)	0.95	(0.75–1.46)	0.94	(0.73–1.65)	0.25	(0.14–0.89)
Interventions I+III	2.80	(1.92–3.08)	1.01	(0.75–1.50)	0.90	(0.73–1.54)	0.20	(0.13–0.88)

*Mean ITAT in days.
†Minimum and maximum ITAT in days.
‡Tissue processing during the day.
§Staggered shifts.
¶Earlier start.
ITAT, intradepartmental TAT; TAT, turnaround time.

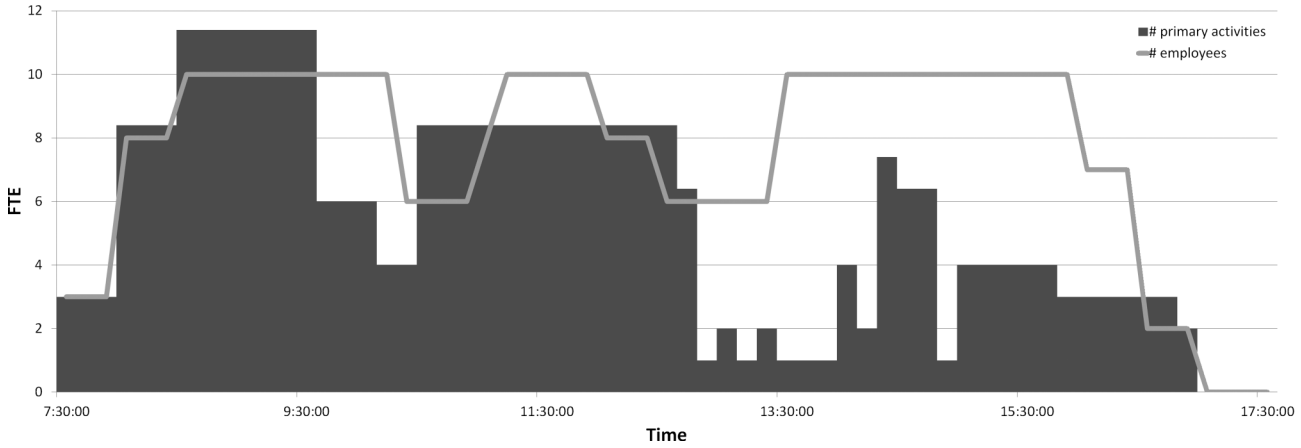

Figure 4 Workload at the baseline situation. The bars indicate the volume of primary diagnostic activities at a certain time. The grey line indicates the number of employees available at that time in the laboratory.

specimens outperformed the average-sized specimens when tissue processing during the day is allowed, even though the average-sized specimens have more strict TAT targets. This is a direct consequence of the lower processing times for tissue-processing batches of small-sized specimens and the moment of arrival of average-sized specimens.

The model showed no significant benefits of staggered shifting in terms of ITAT compared with the baseline situation and the situation with tissue processing during the day. A possible explanation might be that the current number of specimens is not large enough to make this a beneficial intervention.

Reasoning from the principle that workload and staff resources need to be balanced, a more balanced distribution of work over the day can be derived by carefully planning the amount of work over the day, by carefully planning the required staff resources over the day, or by optimising a combination of both. Changing the number of staff resources could result in balanced solutions, for example by adapting the schedules of the technicians to the actual amount of work. By adding more short shifts in the morning and the late afternoon (eg, from 09:00 to 12:00 and 16:00 to 18:00), the peaks in the workload can be covered. However, due to regulations in The Netherlands, there are limitations to flexibility to create early and late shifts, and working before and after regular shifts may require extra compensation. Visualisation of the amount of work corresponding with each of the interventions showed that the tasks as scheduled in the baseline situation are shifted towards other moments during the day when tissue processing during the day was introduced. For example, embedding and sectioning shifted from the morning towards the afternoon. Furthermore, especially on busy days, tissue processing during the day resulted in a more equally distributed workload. A combination of changing the amount of work and the number of resources resulted in the best solutions. This more continuous workflow is likely to be preferred over the traditional batch-mode workflow,[26] as is also well known from other disciplines.[27]

Given the results of the decomposed model, the workflow of the histopathology laboratory of the UMC Utrecht was redesigned. The staff decided to implement interventions I+III, in order to better spread the workload over the day, and assure lower TAT for all patients. As shown in figure 6, even in the proposed situation there is a gap in primary activities in the afternoon around 14:15. Ideally, a batch from the tissue processor should finish at this particular moment. However, due to the low amount of tissue eligible for tissue processing during

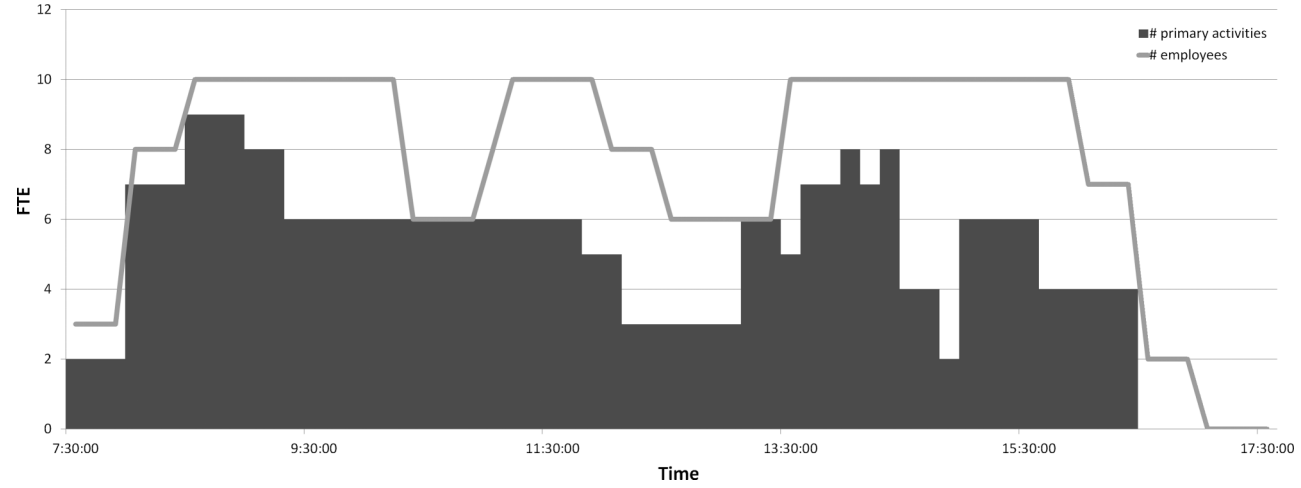

Figure 5 Workload in the proposed situation with tissue processing during the day (intervention I). The bars indicate the volume of primary diagnostic activities at a certain time. The grey line indicates the number of employees available at that time.

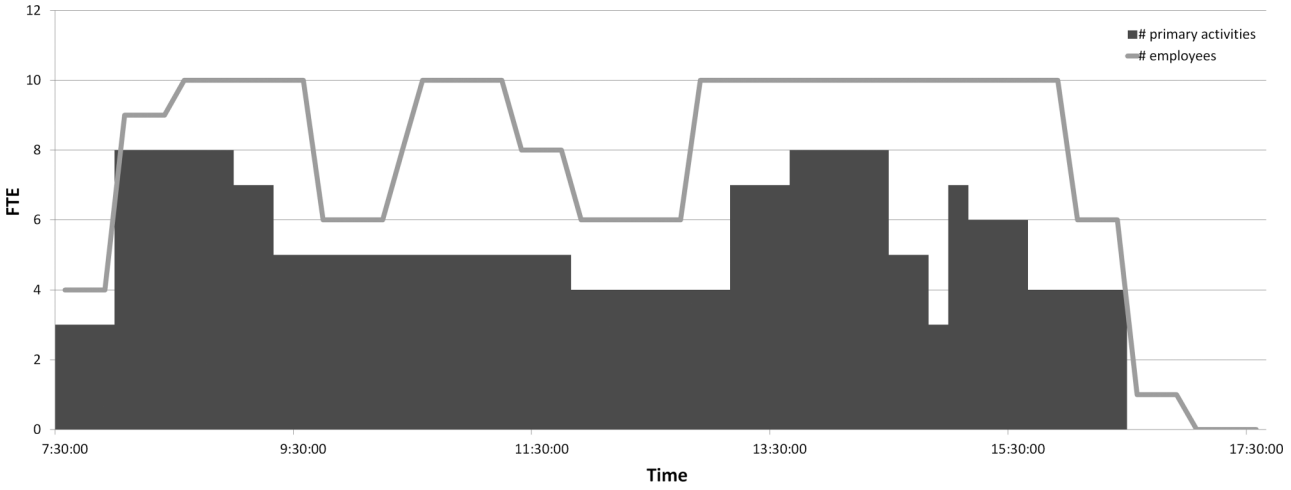

Figure 6 Workload in the proposed situation with tissue processing during the day and earlier grossing (interventions I+III). The bars indicate the volume of primary diagnostic activities at a certain time. The grey line indicates the number of employees available at that time.

the day, this option is currently not feasible in the UMC Utrecht.

Besides the fact that the intervention II did not show any improvements compared with the initial situation in the histopathology laboratory, it was also not adopted because of practical reasons as well. Every time a new technician starts his or her shift, they will inevitably loose some time on social interaction with their colleagues, which is expected to increase with staggered shifts.

Further research should be executed to investigate whether there is a relationship between the quality of work and the more levelled workload. When employees experience less stress during their work, the quality of their work is likely to improve.[7] This can be evaluated by the number of errors and rework, for example in the number of slides that have to be reprocessed and mix-ups. Furthermore, stress levels can be measured before and after interventions.

Besides TAT in the histopathology laboratory, as measured in this study, the hospital's specimen TAT is often measured from the time the biopsy is taken until the time the report is sent to the clinician. The model allows for extensions, for example by including transportation from the biopsy room to the laboratory, and the biopsy itself. However, during this research, it was shown to be hard to include the evaluation of specimens by the pathologists, since many factors influenced this process. Therefore, the process of examination has to become more standardised before it can be reliably modelled.

Same-day reporting becomes more important in pathology.[10] To facilitate same-day reporting, dedicated resources are often assigned to specific specimen categories, which are therefore prioritised. This study showed that in the UMC Utrecht histopathology laboratory, specific specimen types were (unintentionally) prioritised over the remaining specimens. This may have caused other specimen types to underperform, since Vanberkel *et al* have shown that dedicating resources and prioritising categories increases the TAT of the remaining care.[28] Therefore, further research should be done to investigate the presence and implications of prioritisation of specific specimen processing over the remaining care.

Mathematical modelling has shown to benefit in the evaluation of possible interventions before actual implementation. Alternative approaches, such as Lean Management, Six Sigma and TPS (Toyota Production System), also provide tools to level the workload. Even though many of these approaches have shown to have a positive impact in practice,[13 14] these approaches do not allow to evaluate the actual impact of the proposed interventions prior to implementation, with potential threats for the quality of care and quality of work. On the other hand, a combination of mathematical modelling with (one of) these approaches might be even more powerful.

In conclusion, mathematical modelling can help to optimally organise the workload in the histopathology laboratory by assessing the impact of optional interventions. The proposed interventions have been implemented in the histopathology laboratory of UMC Utrecht. Further research should be executed to collect empirical evidence to evaluate their actual impact on ITAT, TAT, quality of work and employee stress levels.

Take home messages

- Histopathology employees face growing demand, which increases the workload during their shifts.
- A 25% decrease in turnaround time in UMC Utrecht's histopathology laboratory can go together with a more levelled workload distribution.
- Mathematical modelling techniques help to evaluate process design of the histopathology laboratory.

Handling editor Cheok Soon Lee

Acknowledgements The authors acknowledge the UMC Utrecht histopathology employees who worked during the execution of this project and implementation of the interventions.

Contributors All authors contributed to the study. The first author wrote the manuscript, while the second till sixth author made corrections to the manuscript. Each author approved the submitted version.

Competing interests None declared.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES

1 Muirhead D, Aoun P, Powell M, *et al*. Pathology economic model tool a novel approach to workflow and budget cost analysis in an anatomic pathology laboratory. *Arch Pathol Lab Med* 2010;134:1164–9.

2 Vernon SE. Continuous throughput rapid tissue processing revolutionizes histopathology workflow. *Lab Med* 2005;36:300–2.
3 Brown L. Improving histopathology turnaround time: a process management approach. *Curr Diagn Pathol* 2004;10:444–52.
4 Buesa RJ. Adapting lean to histology laboratories. *Ann Diagn Pathol* 2009;13:322–33.
5 Stotler BA, Kratz A. Determination of turnaround time in the clinical laboratory 'accessioning-to-result' time does not always accurately reflect laboratory performance. *Am J Clin Pathol* 2012;138:724–9.
6 Schaufeli WB, Bakker AB. Job demands, job resources, and their relationship with burnout and engagement: a multi-sample study. *J Organ Behav* 2004;25:293–315.
7 Fournier P-S, Montreuil S, Brun J-P, *et al*. *Exploratory study to identify workload factors that have an impact on health and safety a case study in the service sector*. Université Laval: IRSST, 2011.
8 Meijman TF, Mulder G, Drenth PJD, *et al*. Psychological aspects of workload. In: Drenth PJD, Thierry H, eds. *Handbook of work and organizational psychology: work psychology*. Hove, UK: Psychology Press, 1998:5–33.
9 Patel S, Smith JB, Kurbatova E, *et al*. Factors that impact turnaround time of surgical pathology specimens in an academic institution. *Hum Pathol* 2012;43:1501–5.
10 Munkholm J, Talman M-L, Hasselager T. Implementation of a new rapid tissue processing method—advantages and challenges. *Pathol Res Pract* 2008;204:899–904.
11 Ribé A, Ribalta T, Lledó R, *et al*. Evaluation of turnaround times as a component of quality assurance in surgical pathology. *Int J Qual Health Care* 1998; 10:241–5.
12 Zarbo RJ, Gephardt GN, Howanitz PJ. Intralaboratory timeliness of surgical pathology reports. Results of two college of American pathologists Q-probes studies of biopsies and complex specimens. *Arch Pathol Lab Med* 1996;120:234–44.
13 Jiang L, Giachetti RE. A queueing network model to analyze the impact of parallelization of care on patient cycle time. *Health Care Manag Sci* 2008;11:248–61.
14 Raab SS, Grzybicki DM, Condel JL, *et al*. Effect of Lean method implementation in the histopathology section of an anatomical pathology laboratory. *J Clin Pathol* 2008;61:1193–9.
15 Zonderland ME, Boer F, Boucherie RJ, *et al*. Redesign of a university hospital preanesthesia evaluation clinic using a queuing theory approach. *Anesth Analg* 2009;109:1612–21.
16 Kallrath J. Mixed integer optimization in the chemical process industry: experience, potential and future perspectives. *Chem Eng Res Des* 2000;78:809–22.
17 Barentsz MW, Wessels H, van Diest PJ, Pijnappel RM, van der Pol CC, *et al*. (2014) Same-Day Diagnosis Based on Histology for Women Suspected of Breast Cancer: High Diagnostic Accuracy and Favorable Impact on the Patient. PLoS ONE 9(7): e103105. doi:10.1371/journal.pone.0103105
18 Van Essen J, Hans E, Hurink J, *et al*. Minimizing the waiting time for emergency surgery. *Operations Res Health Care* 2012;1:34–44.
19 Haupt R. A survey of priority rule-based scheduling. *Operations Res Spektrum* 1989;11:3–16.
20 Gupta S, Karimi I. An improved MILP formulation for scheduling multiproduct, multistage batch plants. *Ind Eng Chem Res* 2003;42:2365–80.
21 Harjunkoski I, Grossmann IE. Decomposition techniques for multistage scheduling problems using mixed-integer and constraint programming methods. *Comput Chem Eng* 2002;26:1533–52.
22 Bisschop J, Entriken R. *AIMMS: the modeling system*. Paragon Decision Technology, 1993.
23 CPLEX II. IBM software group. User-Manual CPLEX 2011;12.
24 Law AM. *Simulation modeling and analysis*. 4th edn. McGraw-Hill, 2007.
25 Serrano L, Hegge P, Sato B, *et al*. Using LEAN principles to improve quality, patient safety, and workflow in histology and anatomic pathology. *Adv Anat Pathol* 2010;17:215–21.
26 Morales AR, Essenfeld H, Essenfeld E, *et al*. Continuous-specimen-flow, high-throughput, 1-hour tissue processing: system for rapid diagnostic tissue preparation. *Arch Pathol Lab Med* 2002;126:583.
27 Womack JP, Jones DT. *Lean thinking: banish waste and create wealth in your corporation*. Simon and Schuster, 2010.
28 Vanberkel PT, Boucherie RJ, Hans EW, *et al*. Efficiency evaluation for pooling resources in health care. *OR Spectrum* 2012;34:371–90.

Predicting turnaround time reductions of the diagnostic track in the histopathology laboratory using mathematical modelling

A G Leeftink, R J Boucherie, E W Hans, M A M Verdaasdonk, I M H Vliegen and P J van Diest

J Clin Pathol published online January 21, 2016