

The cutting edge

Cutting the inefficiency out of paper re-trimming

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It is a commonly appreciated fact that the success of complex operations often depends on being able to think ahead. As a result, the detailed planning of industrial activities absorbs considerable management focus. Although computer-based planning tools are still far from rivaling the analytical flexibility of the human brain, there are more and more tasks where computers perform as well if not better than humans.

In a paper-making plant, the jumbo-reel that comes out of the paper-making process must be cut into smaller rolls to suit the needs of customers. For a human operator to identify the best way to cut such a reel is both time consuming and offers no guarantee of an optimum in respect to avoiding waste or guaranteeing product quality. The problem gains a further degree of complexity when some areas of the paper sheet must be discarded for quality reasons. No two tasks are identical and the possibilities are endless. ABB provides a software package that identifies the best cutting strategy.



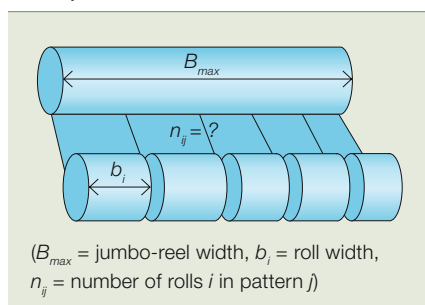
Sensing and controlling

In many industrial processes, there is still much potential for cost-cutting waiting to be tapped simply by implementing better planning strategies in regard to time and raw-material. In this article, an advanced optimization strategy is discussed, which combines offline planning with online quality augmentation. The solution considers quality profiles along the jumbo-reel and the requirements attached to each roll that must be cut from it. A complete geometric solution to this so-called “trim-loss” problem is achieved. The approach presented leads to optimal or close-to-optimal solutions achieving significant savings through tackling quality loss, ie, the economical loss based on degraded product quality. The resulting advantages include reduced energy and raw material consumption, improved reliability in matching customer demands and higher profitability through lower overall production costs.

Cutting paper

A typical paper machine produces a ten meter wide paper sheet at a speed of 120 km/h (or 33 m/s – ie, sufficient paper every second to make more than 5200 A4-sized pages). With a grammage of 80 g/m², this corresponds to 97 tons of paper every hour. The planning of such a process has a crucial impact on the result and its overall efficiency and profitability. ABB already offers an entire, fully-integrated production management suite for paper production including state-of-the-art tools such as leading quality control (QCS¹⁾ and web imaging systems (WIS). Furthermore, ABB’s production planning software is often

1 Jumbo-reel cutting and the trim-loss problem – what is the best way to cut small rolls of specified dimensions from the jumbo reel?



benchmarked as a top-of-the-line solution. It is therefore natural that ABB is seeking ways of making the existing solutions even better and more economical. This ensures that the paper needed is produced as efficiently as possible in terms of production costs, environmental burden and energy and material consumption.

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The cutting of huge “jumbo-reels” into smaller ones takes place at a winder, immediately after the paper machine. The primary objective in cutting problems is to minimize trim loss, ie, the waste that occurs when the full width of the jumbo-reel cannot be used for producing the target rolls. If, for instance, 1.5 m wide rolls are to be cut from a ten meter wide jumbo reel, a 1.0 m wide strip (or 10 percent of the total produced) will go to waste. The problem of trying to combine different roll widths in order to minimize this waste is commonly called the “trim-loss” or “cutting stock” problem. In solving this problem, cutting patterns are identified that are then applied in a slitter by positioning the knives in the desired positions 2. The two most common problem objectives are:

- To find a cutting strategy that produces the required roll widths using as little material as possible, ie, minimizing the trim loss.
- To minimize the number of different patterns and sequence them in such a way that unnecessary knife-setup actions are avoided, maximizing production efficiency.

The approach taken in solving these sometimes contradictory objectives makes a huge difference to the solution that is finally achieved. As the number of discrete settings is vast, the optimization involves challenging mathematics. There are often millions of potential ways of arranging the target rolls on the jumbo-reel. In analyzing these, it soon becomes evident

that there is no practical way of exhaustively testing them, even using the best and most efficient supercomputer. The problem size grows rapidly with the number of rolls due to the large number of alternative cutting strategies. Many heuristic/mathematical approaches to solving such a problem efficiently do exist however, although none of them is guaranteed to deliver the global optimum. Such approaches include rounding heuristics, column generation methods, solving problems only partially and other knapsack-type²⁾ algorithms, to name but a few. Looking at this collection of known approaches, it might seem that the problem is solvable. But would such an approach alone deliver adequate results for the paper-cutting problem?

Considering paper quality

In modern paper mills, the trim-loss problem for the paper machine is commonly solved as an integral part of production planning, well ahead of the actual production of the jumbo reels.

This advanced planning would be quite adequate if it could be assumed that the paper has a uniform quality distribution, ie, to be of optimal quality throughout. Unfortunately, this is not always the case and local quality variations may occur. During the paper-making process, a large amount of data on quality – relating to numerous criteria – is collected from different on-line measurement and scanning devices. These data are then carefully processed and analyzed. Most of the resulting information is available shortly after production of the jumbo-reel has been completed and while it is waiting to be cut or trimmed. In 2, the deviation from target quality is represented by a color code.

When comparing the actual quality distribution with the planned cutting patterns of a jumbo-reel, the predetermined cutting plan may turn out to be far from optimal. For instance, the most valuable customer rolls may have been assigned to the worst positions on the jumbo-reel. If the paper were to be cut in this way, these sections would have to be rejected.

Previous modeling approaches for trim optimization did not support quality-based optimization, as the standard trim-loss problem did not take into account the exact position of each roll in a pattern. It merely focused on the total amounts being produced, ie, how many rolls of a given type each cutting pattern contained.

A novel mathematical programming approach

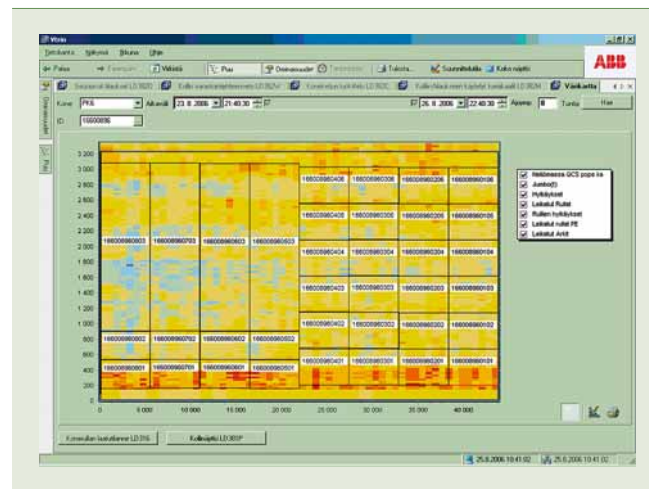
Quality information is collected by the quality control system (QCS) that performs continuous scans along the paper reel. Properties such as moisture, caliper and brightness are measured very frequently – in the cross-direction, typically every 10–50 mm and in the machine-direction every few hundred meters, depending on the speed of the paper machine as well as on the time that the scanning device requires to move across the paper width. In practice, this means that even a small paper machine has tens of thousands of measurement points for each quality criterion.

Another ABB technology is the web imaging system (WIS). In this system, cameras track visual defects (holes, cracks, wrinkles, etc) and the images are efficiently analyzed using neural-network based methods. These ensure fast and reliable processing in the classification and determination of defects.

Besides such online methods and the rapid and accurate information they provide, quality is also analyzed off-line in laboratories. This testing is much more time consuming and is therefore more suitable for tracking certain general quality trends than to observing short-term variations. This monitoring is based on selected samples and can lead to the rejection of a whole jumbo-reel.

Embedding all these quality aspects into a standard mathematical model for the trim-loss problem would increase their complexity further, soon rendering them intractable due to

2 Quality analysis of a jumbo-reel (ABB CPM System)



additional, non-implementable requirements and the large number of discrete decisions. An alternative modeling approach for a quality-based trim optimization is needed. ABB has developed a novel mathematical programming-based approach for auto-

During the paper-making process, a large amount of data – on quality relating to numerous criteria – is collected from different on-line measurement and scanning devices.

matic computation of an optimized solution of the trim-loss problem. The model assumes an existing cutting plan and is able to cover the various quality profiles of a jumbo-reel through a geometric representation

when performing a re-trimming. Driven by tight performance requirements, the mathematical model itself is modular and in the first approach considers one cutting pattern (or trimset) at a time. A re-positioning of the rolls on the set takes into account the exact geometrical position as well as the quality information along the reel width. A second approach looks at the whole jumbo-reel and aims at re-sequencing the fixed cutting patterns in the best possible way. These two approaches can then be arbitrarily combined through an

intelligent algorithm that is also able to include patterns from the whole production run. Splicing and reject-zones are also taken into consideration implicitly. The approach results in optimal or close-to-optimal solutions, reducing the quality loss, ie, the economical loss based on degraded quality significantly. This increases both the profitability of production, as well as the reliability towards customers – a more focused quality management also improves customer satisfaction.

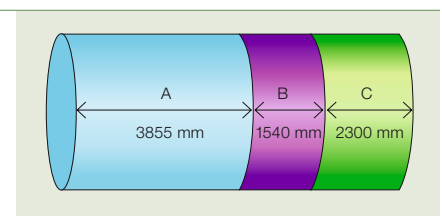
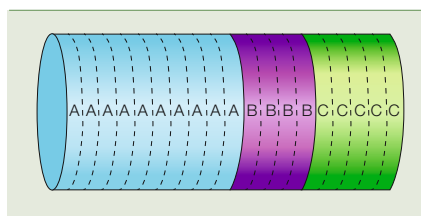
Two steps to success

In order to make this large and very complex problem solvable, the new mathematical approach contains two major steps. In the first step, the jumbo-reel is discretized by dividing it into “slices” **3a**. The quality of each slice is projected to the customer requirements. The resulting optimization model builds on a quality classification, eg, A-, B-, or C-quality. The final

3 Two approaches to finding the optimal way to cut the jumbo reel

a The discrete approach – the algorithm rasterizes the paper, the solution considered can be varied in discrete steps only.

b The continuous approach – dimensions are infinitely variable. This is much more difficult to optimize than the discrete approach of **a**.



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quality for each roll is calculated by combining the quality mapping with key product-roll requirements. This discretization-based method delivers a good approximation to the optimal solution.

The solution is further improved in a second step, which applies a continuous and exact approach, ensuring the feasibility of the final solution. This also allows a smooth adjustment of the edge of each set. The continuous approach builds on dividing the jumbo-reel into continuous quality zones **3b** – or sectors, according to the varying quality classifications of every roll. Each sector is associated with a respective quality (again: A, B, C). Similarly to the first step, this calculation combines the quality mapping with some key parameters of the product roll. This step results in an optimal cutting strategy taking into account the quality distribution along the jumbo-reel.

ABB has developed a novel mathematical programming-based approach for automatic computation of an optimized solution of the trim-loss problem.

Whereas neither of these two strategies alone can always handle more complex problems exactly and efficiently, this two-step approach is both robust and effective. It allows the non-convergent nature of the problem to be circumvented and ensures that a close-to-optimal solution is obtained quickly.

Well-hidden mathematics

The user does not have to deal with any of the underlying mathematics or algorithms. The functionality can be fully integrated into the existing environment; the solution will work silently in the background, creating additional benefits for customers. However, for those readers interested in taking a look “under the hood” some of the main features are explored here.

The approach comprises solving mixed integer linear programs (MILP) within specialized algorithms and utilizes robust and well-established technologies. The mathematical models carry certain similarities to production scheduling, as both feature essential logical decisions. In scheduling, the time-horizon is discretized by a fixed number of gridpoints, which are assigned to jobs through binary variables. In the retrim optimization context, the jumbo-reel width or length takes the place of the time variable.

The solution will work silently in the background, creating additional benefits for customers.

Focussing on the re-trimming of one set, it is assumed that a roll is represented by an index r and each discrete “slice” by j . Then, the binary (zero-one) variable, xd_{rj} , equals one at the jumbo-reel position, j , at which the roll, r , begins (left edge). In order to perform an optimization and maximize the total value of a trim set, a cost coefficient, c_{rj} , indicating the value of the roll at the given position is also required. The objective func-

tion is very straightforward: Define the location for each roll r that maximizes the total value of a trimset. This is expressed in Equation (1) below.

$$\max \sum_{r,j} c_{rj} \times xd_{rj} \quad (1)$$

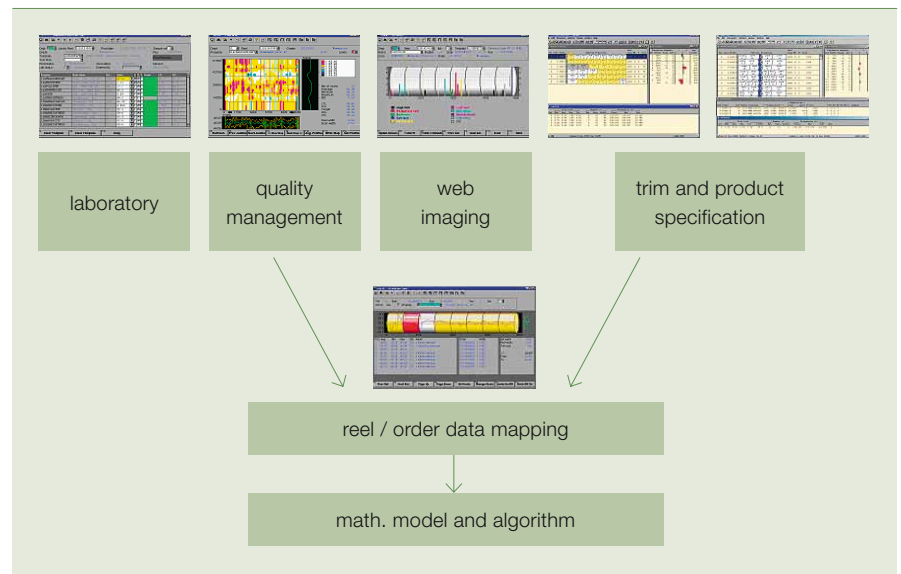
$$xd_{rj} \in \{0,1\}$$

In order to get everything defined correctly mathematically, equations ensuring that no rolls overlap and that each roll must occur exactly once are introduced. Such equations may sound trivial, but sometimes they can become more complex than expected.

The discretized problem results in an optimal cutting plan with respect to a chosen grid density. For typical jumbo-reel widths of up to 10,000 mm, an exact grid (1 mm) would make the problem size intractable. Therefore, a coarser grid (10–20 mm) is selected. In this case, the roll widths have to be rounded down in order to maintain the feasibility of the problem (eg, 578 mm becomes 570 mm when using a 10 mm grid). Such rounding errors are corrected on a consecutive continuous step.

The continuous step also resembles some scheduling strategies, in that it divides the jumbo-reel into flexible slots. These slots are ordered from left to right, and the borders between

4 Cross-application components – many different factors must be considered in finding an overall optimum



them are continuously variable, ie, able to adapt to the respective customer roll widths. Each roll is assigned to exactly one slot and exactly one quality sector through the use of binary variables. In equations (2)–(5) below, the slots are indicated by n and the sectors by s . Thus, a binary variable x_{rn} equals one only if the roll r is assigned to the slot n and similarly, variable x_{rs} indicates that roll r is located at the quality sector s . W_r indicates the roll width, r_r^{start} the position of the left edge of a roll, W_n^B and W_n^E the start and end positions of a slot

and finally, S_s^B and S_s^E the start and end positions of the sectors.

$$W_n^E = W_n^B + \sum_r x_{rn} \cdot W_r \quad (2)$$

$$r_r^{start} = W_n^B \text{ if } x_{rn} = 1 \quad (3)$$

$$\sum_s x_{rs} = 1 \quad (4)$$

$$S_s^B \leq r_r^{start} \leq S_s^E \text{ if } x_{rs} = 1 \quad (5)$$

$$x_{rn}, x_{rs} \in \{0,1\}$$

In short, Eq. (2) adjusts the width of a slot according to the roll that has been assigned to it. The slot should start exactly at the left edge of its roll, which is enforced in Eq. (3). The fact that one roll can only belong to one quality sector is expressed in Eq. (4) and finally the roll must be positioned within this sector, as indicated by Eq. (5). These are just some key constraints of the problem illustrating some of the main mathematical and logical dependencies.

An intelligent algorithm can reduce the quality losses to a physical minimum. This ensures that the current planning is always up-to-date with respect to the known quality data.

Algorithm for putting it all together

The components discussed in the previous sections are visualized in 4. More important than mastering the mathematical details of the model is understanding how everything can be put together into one robust and uniform concept. To illustrate this, the original problem is reconsidered. The mathematical modeling aspects presented above, combined with the two-step approach allows an efficient solution of the quality-based re-trimming problem. The resulting strategy can be applied in various ways: Re-organization can be executed one set at a time 5a, or by changing the sequence of sets in a jumbo-reel 5b.

In the former case (focus on one planned trimset), the set is adjusted so

that the rolls are re-positioned in order to maximize the total value (quality yield), thus minimizing the effect of quality deviations. A simplified example of this would be to place the most valuable roll onto a good region. In 5a, the red color indicates that the roll must be rejected and the yellow color stands for minor quality deviations (B-quality).

The same technique can be also utilized to re-sequence the sets in a jumbo-reel 5b. Following the above principle, by combining the quality distribution information with the jumbo-reel cutting plan, it is possible to improve the quality yield. This is achieved by placing the sets into positions where the total value is maximal.

An intelligent algorithm that solves these two problems in a given sequence can reduce the quality losses to a physical minimum. This ensures that the current planning is always up-to-date with respect to the known quality data. Automatic jumbo-reel splicing and reject zones in cross-direction can also be implemented into the solution, as well as considering patterns from the whole run. To round it off, the cross-application between production planning and quality management offers additional possibilities for making the production both economically and environmentally more attractive.

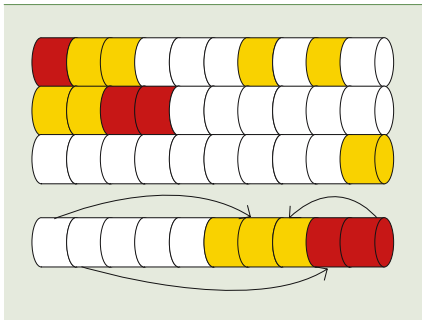
Illustrative example

In the following section a simplified example is discussed. A trimset with the roll widths of the Factbox of page 58 is assumed.

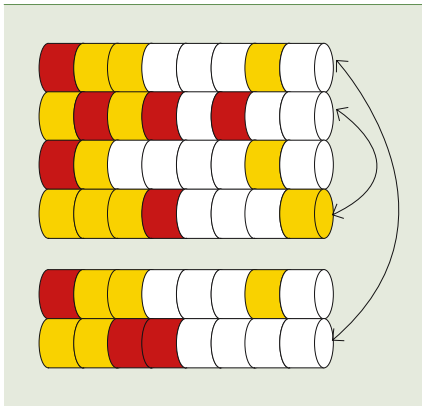
The example jumbo-reel has a trim width of 8000 mm. The sum of the roll widths to be trimmed is 7915 mm, which results in a trim loss of 85 mm. Here, each roll is assumed to have exactly the same quality requirements. Therefore, the example can be simplified by directly dividing the jumbo-reel into various quality zones. If a roll spans over several quality zones, it is valued according to the worst quality. For illustrational purposes, a quality distribution is shown in 5a, in which the quality is expressed in terms of A-, B-, and C-quality. For the

5 Optimization approaches

a Adjusting one set



b Changing the sequence of sets



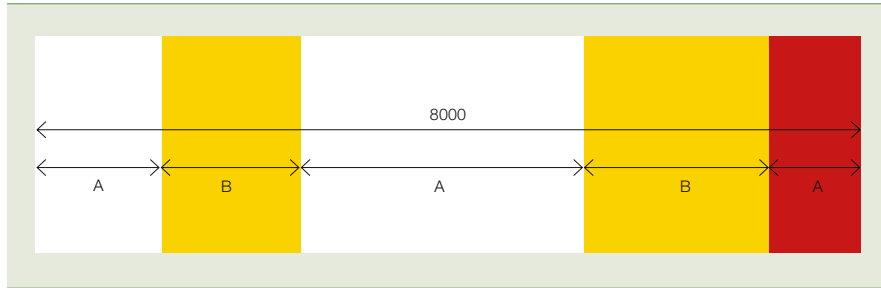
Paper rolls unloaded from the winder ready for packing



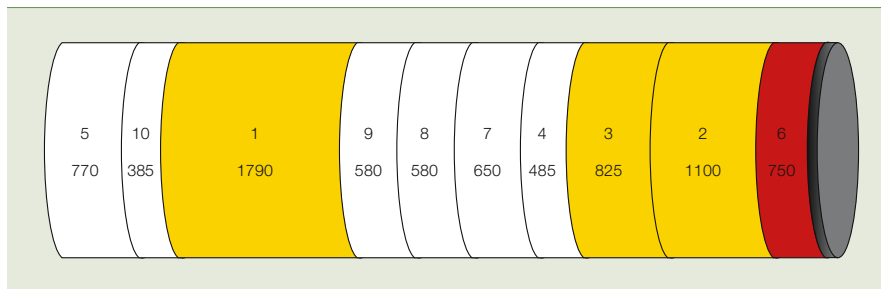
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6 The reel quality map

a The problem



b The resulting trim set (quality: A=white, B=yellow, C=red)



Factbox Data for example above (roll widths)

Roll	1	2	3	4	5	6	7	8	9	10
Width (mm)	1790	1100	825	485	770	750	650	580	580	385

optimization problems reported here, the value of each roll is calculated based on the following assumptions: Set length = 5896 m, paper weight = 80 g/m², price = 500 €/ton, A-quality (full quality) = 100 percent of price, B-quality (minor defects) = 70 percent of price and C-quality (rejected) = 0 percent of price.

Using no optimization, but just ordering the rolls on the set as given in

Nomenclature

x_{dj}	= 1, if roll r starts at gridpoint j
c_{rj}	= value of roll r at gridpoint j
x_{rm}	= 1, if roll r is assigned to slot n
x_{rs}	= 1, if roll r lies in sector s
r_r^{start}	= left edge of roll r
W_r	= width of roll r
W_n^B	= start (left edge) of slot n
W_n^E	= end (right edge) of slot n
S_s^B	= start (left edge) of quality sector s
S_s^E	= end (right edge) of quality sector s

Factbox would result in a total profit of 1236 €. The quality-based re-trimming algorithm finds the solution 1427 € [6], which corresponds to an improvement of around 15 percent. The efficiency of the optimization can be tuned and there is always a tradeoff between solution quality and efficiency. However, the combined strategy gives a good result within a reasonable time.

The set is adjusted so that the rolls are re-positioned in order to maximize the total value (quality yield), thus minimizing the effect of quality deviations.

Cutting out waste

The solution discussed will not eliminate quality problems, but will minimize their effect by ensuring that planning is always geared towards the most profitable option and is able to make most out of the current quali-

ty. Furthermore, increasing the awareness of quality may also improve the overall planning culture and thus strengthen the capability to identify and analyze production efficiency with respect to quality.

The primary objective in cutting problems is to minimize the waste that occurs when the full width of the jumbo roll cannot be used for producing the target rolls.

Reduced quality losses mean:

- reduced production times
- less recycling of rejected rolls
- reduced energy and raw-material consumption
- better commitment to customer quality requirements
- more reliable delivery dates
- minimal environmental impact
- lower total production costs
- fewer quality complaints
- increased customer satisfaction

These sound very trivial. In fact, the proposed solution contributes to making these considerations part of everyday standard operation.

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Footnotes

¹ QCS: Quality Control System

² The knapsack problem is a combinatorial optimization task, the goal of which is the identification of the subset of a given set of objects so that the sum of their values is as close to a given limit as possible without exceeding it. The name derives from an example in which as many objects as possible are to be fitted into a knapsack of limited size.