Preferred citation: K. Ebeling. Product/process analysis as tools for selecting/optimising the papermaking process. In **Fundamentals of Papermaking**, *Trans. of the IXth Fund. Res. Symp. Cambridge, 1989*, (C.F. Baker & V. Punton, eds), pp 367–382, FRC, Manchester, 2018. DOI: 10.15376/frc.1989.3.367.

PRODUCT/PROCESS ANALYSIS AS TOOLS FOR SELECTING/OPTIMISING THE PAPERMAKING PROCESS

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Mr Chairman, Ladies and Gentlemen,

I feel greatly honoured to have this opportunity to sum up this 9th Fundamental Research Symposium. Apparently some concern had been expressed that this Symposium might be considered as an internal James River symposium instead of an international symposium, if both the Guest Speaker's Opening Remarks and the Summing Up of the Symposium were to be presented by James River representatives.

The objective of my presentation is to evaluate the various contributions of this Symposium as to how they fit the deeper understanding of the technological foundations of papermaking and the scientific foundations of the structural behaviour of paper. The opinions I will be presenting are totally my own, and I will accept very little - if any - responsibility for them.

What have we been dealing with during this symposium? The answer is simple: "With the manufacture of coated printing papers!" Of course the reviews and the other presentations also apply to the manufacture of other types of papers as well.

The manufacture of coated magazine paper is shown in Fig. 1 as a block diagram. Excluding the manufacture of mechanical pulp, the <u>various review papers</u> of this Symposium cover most of the important subprocesses and critical scientific phenomenon of LWC papermaking in a very comprehensive manner. They also point out potential areas for future research. The <u>other presentations</u> of this Symposium support the advancement of our understanding of these subprocesses or their effect on paper structure. Perhaps the only areas that have not been dealt with extensively in this symposium are:

(a) raw material characterization and (b) end-use characterization of paper.

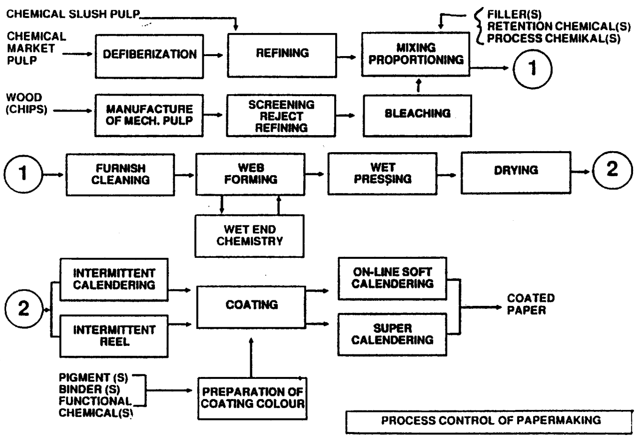

Figure 1. Simplified block diagram for the manufacturing process of LWC paper.

How does one utilize all this information? How does one synthesize - from this vast volume of detailed analytical information - the needed **relevant** pieces of information for a particular papermaking process or product? That is, how does one focus on what is important for the manufacture of a certain paper or paperboard grade?

Let me introduce you to two practical tools: **product analysis** and **process analysis** (1), which, - according to my experience, have been very handy in focusing on the relevant questions in advancing papermaking and in developing new products.

CENTRAL ROLE OF PAPER STRUCTURE

The structure of paper depends on three different groups of "engineering" variables as seen in Fig. 2.

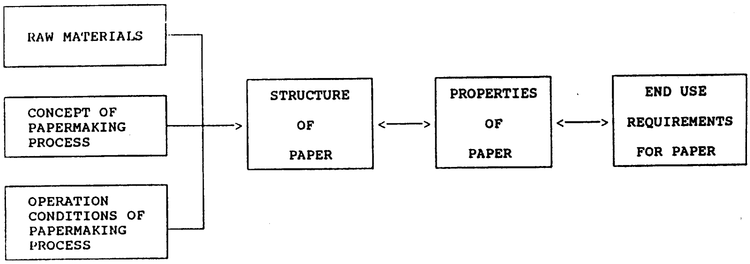

Figure 2. Cause and effect relationship in papermaking.

The first group of variables represent raw materials, for example fibers and pigments. The second group of variables represent process concepts, for example: "Is one using a fourdrinier papermachine or a twin-wire papermachine", or in board making; "Is one using a multiwire paperboard machine or a fourdrinier papermachine", or in calendering; "Is one using an on-line soft nip calender or a conventional supercalender?" The third group of variables represent the operation conditions of the papermaking process (consistency, specific edge load, net energy expenditure of refining, amount of retention chemical(s) and the(ir) point(s) of addition, landing geometry of the jet, drainage profile on the wire, addition point and amount of steam in supercalendering, etc.). We can also call this last group of papermaking variables "know how" parameters. Thus, the structure of paper or paperboard depends on (a) raw materials, (b) process "geometry", and (c) "know how" (fig. 2).

The structure of paper defines its properties, and the properties define the suitability of paper for a specific end-use, i.e. the paper properties define its functional suitability.

PRODUCT ANALYSIS

How do we know what type of a structure a paper should have for a certain end-use? Or, how do we know the key properties that the satisfactory paper grade needs to have?

In order to answer these questions one needs to carry out a **product analysis**, i.e. to obtain proper market and customer information and to assess from this collected data the **relevant** property requirements (**important product attributes**) for a satisfactory end use (Fig. 3) (2).

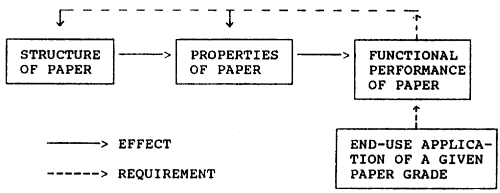

Figure 3. Schematic representation of interplay between structure and performance of paper.

Simplified Example

The product analysis is initiated by "asking" what major job(s) the paper grade in question has to "do" in order to be a high quality paper. This questioning will lead to one or several functional properties (product needs/product attributes) that the paper has to fulfil in order to do "its job" properly.

As an example of product analysis one could take a gift shop wrapping paper. An answer to the question: "What is the job of this paper?", would be: "Its job is to be easily wrappable, to protect the contents of the wrapping, and to provide a surface for fairly high quality advertisement (visual impression of printed message).

In fullfilling its wrapping job the high quality wrapping paper should have sufficient strength during the wrapping operation. In fulfilling its protecting job, the high quality wrapping paper should also have sufficient strength. In order to fulfill its advertisement job the high quality wrapping paper should have good printing paper characteristics and a glossy look at least on one of its surfaces.

The qualitative information obtained above is not sufficient to demonstrate how good the paper grade in question is. One needs quantitative values to judge how good the quality of paper really is or if the quality of the paper has stayed constant over a longer period of time. Therefore measurements need to be carried out in order to put a quantitative value to the important properties found by the product analysis (Fig. 4).

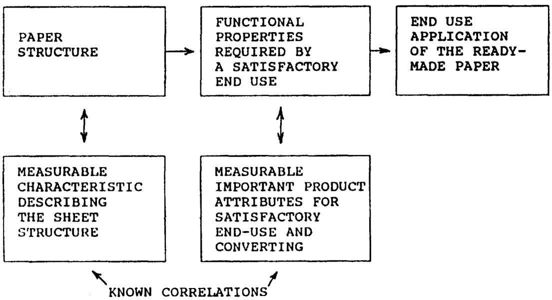

Figure 4. "Flow diagram" of Product analysis.

In the above example one could select the following measurements to characterize the important product attributes and structure of the gift wrapping paper (Table I).

TABLE I. **SIMPLIFIED PRODUCT ANALYSIS FOR GIFT SHOP WRAPPING PAPER**

END-USE APPLICATION OR FUNCTION	CORRESPONDING VERBAL CHARACTERIZATION FOR SATISFACTORY END-USE	RELEVANT MEASUR-ABLE IMPORTANT PRODUCT ATTRIBUTE
GIFT WRAPPING	PAPER POSSESSES SUFFI-CIENT STRENGTH AND BENDS AND FOLDS WELL	TEAR STRENGTH BEND. STIFFNESS
CONTENT PROTECTION	PREVENTS DAMAGE TO CONTENT CAUSED BY PACKAGE TEARING OR RUPTURE	TEAR STRENGTH T.E.A PUNCTURE RESIS-RESISTANCE
DELIVERY OF PRINTED MESSAGES OR VISUAL IMPACT	PROVIDES GOOD SURFACE FOR HIGH QUALITY PRINTING AND VARNISHING	FORMATION SMOOTHNESS BRIGHTNESS ABSORBENCY

In the above example it is important to remember, that if the gift shop wrapping paper is pigment coated, the coating process also requires certain structural features from the base paper so that a satisfactory coating result will be obtained. Therefore, instead of merely asking what type of "jobs" the paper needs to perform from the viewpoint of the end-use application, it is important to include also those reguirements that the converting process sets for the (base)-paper.

One should, however, keep in mind that there are numerous ways to characterize both the structure and the important product attributes of paper or paperboard. This is because of the structural heterogeneity and 3-D directionality of the structure. In order to keep the characterization of the structure and of the important properties at a minimum one needs to concentrate on the very essential features of the structure and properties, i.e. to carry out a relevant characterization (Fig. 4). What is relevant, is determined, to a very large extent, by the **end-use application** of the paper or paperboard and by the interrelated **functional property requirements** as depicted in Fig. 3.

Since papermaking is also a money making process, it is important to include manufacturing cost or related information as a relevant product attribute when carrying out product analysis for a given grade of paper or paperboard.

Structural Considerations

Although several significant correlations exist between the structural properties and the functional properties, the quantitative relationships are meager (Fig. 4). Therefore, the same focus for relevancy is also needed, when one wants to characterize the structure of paper. Examples of structural characteristics could include - for instance - how the fibres and fillers are distributed through the thickness of the sheet, how the fibres are bonded to each other, oriented and flocculated, and how the frozen in stresses are distributed in the fibre cell walls and how the fibre cell wall fragments are distributed around the periphery of the interfibre bonds. These relevant pieces of structural information are helpful in optimizing the existing papermaking process and in selecting the most suitable raw materials. In the case of a new manufacturing process the same relevant pieces of information are needed for the selection of the most appropriate process equipment, raw material and operation conditions (Fig. 2). Fig. 5 depicts an example of the connections between the structure of paper and its important product attributes. This example is for a rotogravure grade supercalendered magazine paper (2).

There are several examples in the literature for carrying out **product analysis.** Hill (3) has analyzed the property requirements for business forms, Humphrey (4) for non-impact printing papers, Campbell and Borch (5) for thermal transfer papers, Walkden (6) for continuous forms bond, Ebeling and Laine (7) for release base paper, Paulapuro (2) for supercalendered magazine paper, Holm and Paulapuro (8) and Haarla (9) for LWC paper.

PROCESS ANALYSIS

After **product analysis** one carries out **process analysis.** The purpose of the **process analysis** is to find out the **criticacal control parameters** of the papermaking process. But first, let us shortly review the various ways to affect the structure of the paper or board.

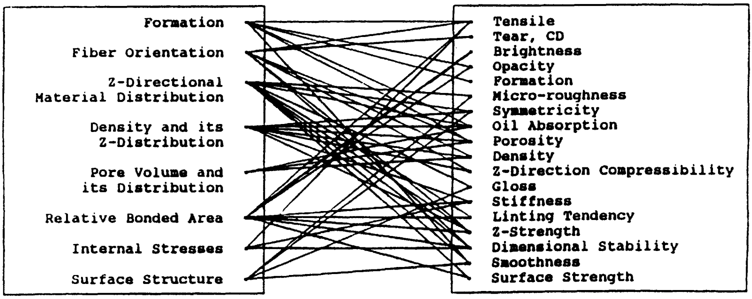

Figure 5. Schematic presentation of interconnection between structure and important properties of SC-rotogravure paper (2).

Control Principles for Papermaking

One can usually differentiate between three types of control principles for the manufacturing process in order to get the required paper (or paperboard) structure. These control principles are based on:

- active control variables
- passive control variables
- constitutive control "variables"

Table II Outlines examples of these three principles.

Table II. **EXAMPLES OF VARIOUS TYPES OF PROCESS CONTROL PARAMETERS**

TYPE	EXAMPLES
ACTIVE CONTROL	
REFINING:	GAP BETWEEN ROTOR AND STATOR
WET PRESSING:	NIP LOADING
CALENDERING:	NIP LOADING
PASSIVE CONTROL	
REFINING:	TYPE OF TACKLE
DEWATERING:	ADJUSTMENT OF DRAINAGE ELEMENTS
WET PRESSING:	ROLL DIAMETER, ROLL COVER
SUPERCALENDERING:	ROLL HARDNESS, GEOMETRY OF STEAM SHOWER APPLICATION
CONSTITUTIVE CONTROL	
MECHANICAL PULPING:	SELECTION OF PROCESS (GW, PGW, TMP, CTMP)
REFINING:	LOW OR HIGH CONSISTENCY
PAPERMAKING:	FOURDRINIER Vs. TWIN WIRE
COATING:	SDT OR APPLICATOR ROLL TECHNOLOGY

Only the active control variables are controllable at will and continuously available for process control and process optimization purposes. The use of passive control variables requires a maintenance stop and the availability of alternative equipment or the possibility for geometrical (or corresponding) process adjustments. The use of constitutive control parameters requires a major capital expenditure decision. Usually such a decision involves that at least part of the manufacturing process will be replaced by newer technology.

The active control parameters are the ones that are normally included in the **process analysis.** However, in developing a new paper grade or starting to utilize a new raw material, one can also use the passive control parameters and the constitutive parameters. The process analysis procedure is also very useful in developing a quality control system for the papermaking process (8) and in pinpointing the most probable causes of disturbance in trouble shooting a papermaking process.

Procedure for Process Analysis

Fig. 1 outlines a schematic block diagram of the manufacturing process for LWC paper. It also contains the manufacturing process for mechanical pulp.

Each of the depicted "unit operations" of Fig. 1 contains both active and passive process control variables. Thus one can state that each subprocess (unit) operation actually forms an input output relationship, where the input to the subprocess consists of the "state variables" of the process in the previous stage(s) (= process conditions or property values of the process flow). The output consists of the values of the "state variables" at the end of the corresponding subprocess. The input output relationship of the various depicted subprocesses may not be very quantitative especially if the subprocess has a tendency to cause disturbances in the process.
It is a rule in papermaking technology that certain cause and effect relationships between the control parameter of the process and the product attribute (property or a subprocess "state variable") are universal. The gradient of the obtained effect may vary considerably between the manufacturing processes for the various paper grades.

If one would have to systematically evaluate all the possible combinations of the control parameters of the block diagram of Fig. 1, the needed experimental program would be gigantic even if carried out in the laboratory scale.

In optimizing the manufacturing process for a given paper grade one carries out a **process analysis**. The purpose of the **process analysis** is to identify those active control variables that will have a critical action on the important product attributes (including manufacturing cost or related information). A critical control action is such, where the adjustment of the active control variable causes a positive effect in some of the important product attributes and a negative simultaneous effect in some other important product attributes. Refining is a good example of a critical control variable, since increased refining increases tensile strength, but decreases opacity and dimensional stability. In other words, tensile strength and opacity form a critical pair of important product attributes for many printing papers, i.e. it is impossible to increase both of these properties by increased refining.

The practical identification of the critical active control variables is best carried out in a matrix, i.e. in the **product analysis vs. process analysis matrix** (Fig. 6). Sometimes this matrix is called the RYTI matrix, because it apparently was prof. Niilo Ryti, who first used this technique in a systematic way (**10**).

The axis of the RYTI matrix are formed as follows:

1a. List the important product attributes obtained through **product analysis** as column headings.

1b. Include also such process "state variables" or their combinations that describe economic aspects of the papermaking process (for instance; refining or grinding energy, solids content of the web after wet pressing, paper machine speed, need for expensive pulp, chemical or pigment).

2. List the most significant control variables of the process. Place this listing in the vertical position to the left side of the matrix.In listing the most significant active control variables of the process one should use some experience so that the process analysis list does not become too excessive (vertical colum of Fig. 6).

After the horizontal axis and the vertical axis of the matrix have been constructed, one needs to identify the cause and effect "direction" that an increased control action of a selected process variable will have to the selected important product attributes. Usually one marks a positive effect of an increased control variable action with a + sign, and a negative effect with a - sign. If a selected active control variable has both + and - effects to the listed product attributes and to the cost information, then that control variable is a critical control variable.

Practical Example; Gift Wrap Paper

Fig. 6 outlines - in a simplified form - the final matrix form of the **product vs. process analysis** procedure. The horizontal matrix axis consists of those product attributes that were derived in connection Table I. The vertical matrix axis depicts those process variables that can be used to "control" the important product attributes. The selected variables cover raw material, sheet forming, and surface application plus calendering. The + and - signs in the matrix point out the advantageous or disadvantageous changes in the important product attributes that result from an increased "control action" of a given process control variable. Fig. 6 shows that all the depicted control variables are **critical.**

Important Product Attributes

SIGNIFICANT "CONTROL" VARIABLES OF THE PAPERMAKING PROCESS .... Effect of Increased Action of Control Variable on -->	Wrapping		Pro-tec-tion	Printability					Cost	
	Tear Strength CD	Bend. stiffness	Puncture resistance	Formation	Smoothness	Absorbency	Brightness	CD dimensional stability	Contribution to manufact. costs	Nature of "control" variable
Amount of Bl.SWKP	+		+	-	-			-	-	critical
Refining of Bl. SWKP	-	-	+	+	+	+	-	-	-	critical
Amount of high brightness pigment	-	-	-	+	+	+	+	+	+	critical
Jet-wire Δ speed	±			±	±	±		±		
Position and Δ speed of dandy				±	±	±				
Amount of surface sizing		-	+			+	-	+	-	almost critical
Amount of coating layer					+		+			
Supercal.line press.	-	-	-		+	+	-			critical
Supercal. moisture	-	-	-		+	+	-			critical
Supercal. temp.	-	-	-		+	+	-			critical

\+ = Advantageous change in product attribute
\- = Disadvantageous change in product attribute

Figure 6 Simplified product vs. process analysis for gift shop wrapping paper.

The available time does not allow me to describe the RYTI matrix using more elaborate examples, but such examples are found in the literature. Ryti & Aaltonen describe the product vs. process analysis for the top layer of folding cartonboard (1), Paulapuro for SC magazine paper (2), Holm and Paulapuro (8) and Haarla (11) for LWC paper, and Ebeling and Laine (7) for release base paper.

Process optimization

The optimum manufacturing for a given papermaking process is that set of operating conditions for the active process control variables which produces acceptable quality with minimum costs, or which enhances the values of the important product attributes with a minimum increase in manufacturing costs. The skilful use of the product vs. process analysis technique allows the papermaker also to obtain the continuous **"Golden Arrow"** transformation (Fig. 7), which was introduced by Mr. R.C. Williams in his Guest Speaker's address.

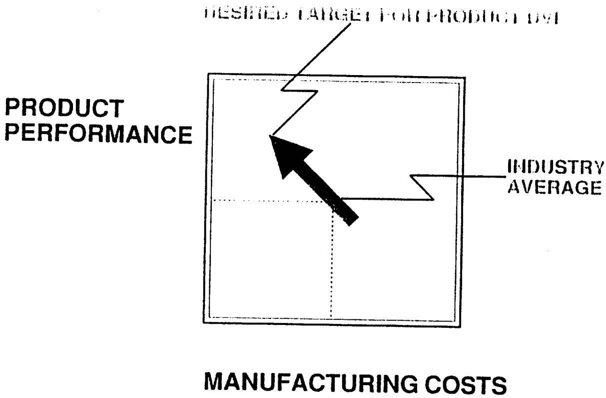

Figure 7. Product and process analysis as tools for technology advancement, i.e. for "Golden Arrow" activity.

The practical optimization - once the critical control variables have been identified - involves experimental design and handsheet studies. References (12) and (13) depict typical experimental designs involved in these type of experiments. Also the examples of product analysis previously referred to contain examples of the actual optimization experimentation (7,11).

Once the laboratory scale optimization has been carried out, one may wish to verify the results on a pilot paper machine scale. The results obtained from the pilot paper machine study usually are quite applicable to full scale papermaking, but in some cases further optimization with a full scale papermaking process is needed.

Final Remarks

In summary one may state that the described **product** and **process analysis** matrix treatment with successive laboratory and pilot paper machine scale experimentation provides the most suitable raw material mix and/or the optimum operating conditions of the manufacturing process for a given paper/paperboard grade (Fig. 2).

The outlined methods can also be used in product development work and in assessing development needs for today's manufacturing processes. This is so, because the combination of the product analysis and of the process analysis into a matrix form helps one to identify those critical pairs of important product properties, i.e. fundamental inverse inter-property relationships, which often hinder the achievement of superior product performance. The above matrix analysis also identifies those critical subprocesses, where process development work might be most beneficial in obtaining superior product performance.

In this connection I would also like to emphasize that, in my belief, product development and process development are not two different and nonrelated R & D activities. They are closely linked to each other through the product analysis/process analysis interface. In a succesfull R & D operation one cannot exist without the other. One may also conclude, that in the case of investment decisions a **product analysis vs. available technology analysis** can be carried out exactly in an analoguous manner in order to reach the best possible investment decision for the manufacture of a given paper or paperboard grade.

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