MANUFACTURING PROCESS ADAPTATION FOR THE INTEGRATED COST/WEIGHT OPTIMIZATION OF AIRCRAFT STRUCTURES

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ABSTRACT

Composite materials can be used in primary structures of an aircraft if a cost-efficient design is applied. In earlier work, a cost/weight optimization framework has been presented. This is now enhanced by a module that minimizes the manufacturing cost in each iteration by the adaptation of manufacturing parameters. The framework itself is modular and applicable to arbitrary parts and geometries; therefore, commercially available software modules are used. The framework extension is added to an existing cost/weight optimization implementation and tested on an airliner center wing box rear spar. Three optimization runs are performed, and a low-cost, an intermediate and a low-weight design solution are found. The difference between the two antagonistic solutions is 4.4% in manufacturing cost and 9.7% in weight. Based on these optimization trials, the effect of the parameter adaptation module is analyzed.

1. INTRODUCTION

As the price for jet fuel rises, the airliner's fuel consumption has to be reduced in order to offer a competitive product in terms of operating cost. One way to cut the fuel consumption is to lower the gross weight, thus increasing the performance of the aircraft structure. Composite materials can lower the structural weight significantly; the drawbacks, however, are increased manufacturing costs. The minimum weight and the minimum cost solution are two extremes that often contradict each other; therefore an optimal design solution is a tradeoff between the manufacturing cost, structural requirements, process capabilities and the material available. A measure of the quality of a design solution is the direct operating cost (DOC) where the cost of flight, depreciation, maintenance, etc. are added to one value.

In Kelly et al. [1], Wang et al. [2], Curran et al. [3, 4] and Kaufmann et al. [5], a weight penalty approach for the optimization of aircraft structures was incorporated. All these approaches have in common that the objective function is formed by weighted sums, the latter containing the manufacturing cost and the weight of the part. In particular, Kaufmann et al. proposed a simplified direct operating cost as the objective function; it contains the manufacturing cost and the life fuel burn costs as the geometry-driven attributes of aircraft components. Other costs that appear during the lifecycle of the aircraft (see [6]), such as cabin cost, navigation cost, maintenance and repair and dismantling costs were neglected. This objective function can be written as

$$DOC = C_{man} + p \cdot W. \qquad (1)$$

The manufacturing cost C_{man} covers all operations to produce the part, from tooling to surface finish along with associated labor and material costs. It also includes costs for assembly. The second component, the cost of fuel burn, is related to the mass of the part and can therefore be expressed using the lifetime fuel burn cost per kg aircraft mass p set against the computable part weight W. Additionally, it has to be considered that any candidate design must fulfill the structural requirements of the specified part while aiming for the DOC minimum. This leads to the optimization problem as

$$\begin{array}{lll} \min & DOC & \\ \text{subject to} & \text{structural requirements} & \\ & \underline{x}_i < x_i < \overline{x}_i & i = 1 \ldots n \end{array} \quad (2)$$

with n geometric variables x_i that are allowed to be within the limits $\underline{x}_i$ and $\overline{x}_i$.

The weight penalty p may have a decisive impact on where the cost/weight minimum is located. Wang et al. proposed a value of \$500/kg, whereas comparable values of Curran et al. tend to be much lower (\$86-150/kg). Vogelesang and Gunnink [7] quote a cost reduction of €19.2 to €43.5 per year per kg weight saving. On a life span of approximately 25 years, this value would accumulate to €481 to €1087 per kg saved weight. Eventually, an own estimation has been performed based on current fuel prices and fuel consumptions of Scandinavian Airlines' airliners[1], resulting in €1500/kg to €2000/kg.

The optimization problem (2) is applicable to arbitrary components of aircraft structure, such as the skin/stringer element presented in [5]. There, the authors concluded that a major drawback of the proposed work is the locked manufacturing processes as they have been declared beforehand and remain the same during every iteration of the applied optimization routine. The stiffener geometry, for example, could be manufactured in different ways, and the choice of tools (cutter material and size) has an influence on the manufacturing costs and should not be kept constant during the optimization. Therefore, the process conditions or parameters such as tool specifications, machine properties or even inspection methods could be adapted in order to achieve the lowest possible manufacturing cost for a given geometry. Such a parameter adaptation is illustrated in Figure 1.

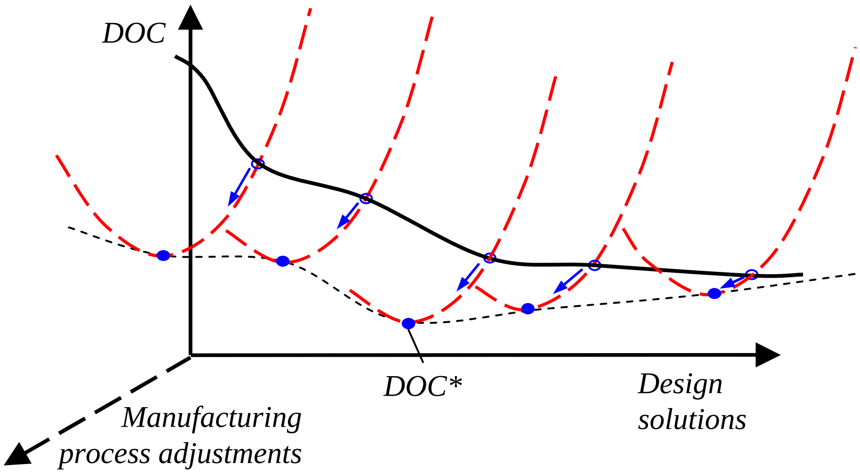

Figure 1: Further minimization of direct operation cost through adaptation of process adjustments

The thick line shows the objective function value depending on feasible design solutions without adapting the manufacturing process to these particular solutions. The dashed line illustrates the optimized DOC values through process adaptations, whereas each of the five parabolic curves illustrates the scope of process adjustments for a par-

[1] personal communication with Olle Björk from Scandinavian Airlines, Sweden; April 25, 2007

ticular design solution. The optimization potential for each design is indicated by the arrows and points, respectively.

2. METHOD

The optimization framework proposed by Kaufmann et al. [5] was used to optimize the design of skin/stringer elements by linking a CAD model (ABAQUS CAE), a manufacturing cost model (SEER-DFM) and results of a finite element analysis (ABAQUS Standard) of the part as illustrated in Figure 2. For further information on these tools see [8, 9] and http://www.galorath.com.

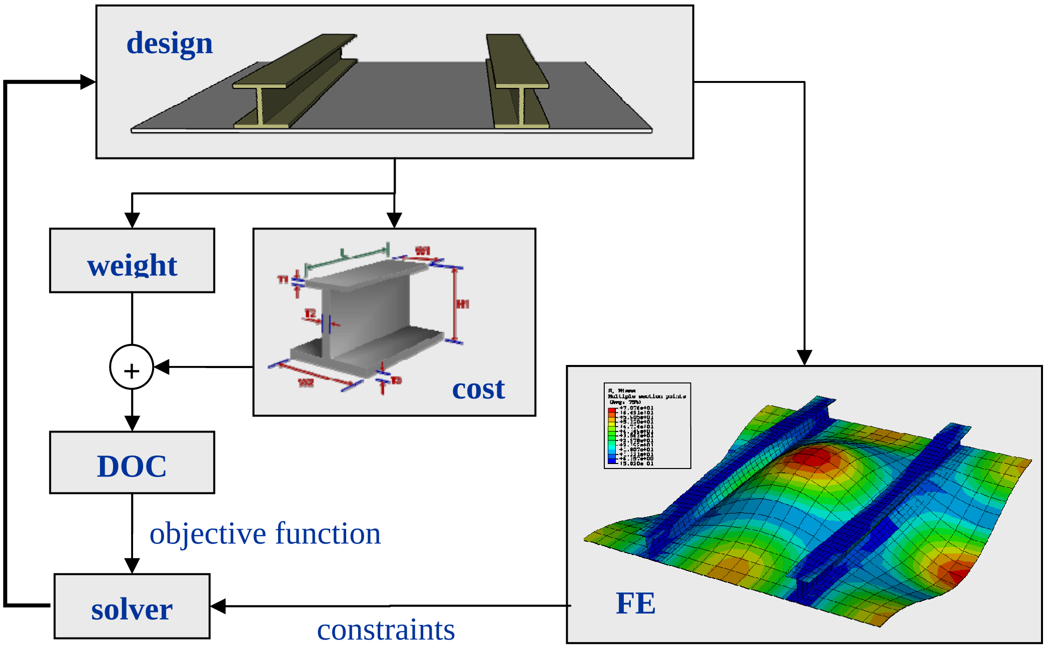

Figure 2: The optimization loop.

In order to automate the cost calculation, the SEER-DFM server mode is used for the manufacturing cost modeling. The skin/stringer element cost is modeled once and the information needed to build that model is exported in the form of a command file. In every iteration, this file is then altered according to the variable changes made by the solver. Thereafter, the manufacturing cost C_{man} are calculated and fed back. The finite element analysis for each given design solution is done with ABAQUS/CAE, where the structural model is parameterized in the form of Python scripts[2]. The solver synchronizes the two parts of the loop and controls the overall process. A gradient-based optimization method (Method of Moving asymptotes, see [10-12]) has been chosen for that purpose. It is implemented in the tool Xopt (see Alfgam AB [9]).

2.1 Framework Extension

The idea of the parameter adaptation was incorporated into the existing framework concept. For this task, a subroutine is integrated into the scheme described, optimizing the process within SEER-DFM while keeping the geometrical design, defined by the variables x_i, unchanged. For the incorporation of process knowledge and the retrieval of appropriate process options, facts and rules have to be stored in the form of a knowl-

[2] see http://www.python.org

edge base. A second solver is needed to process the design information and the stored knowledge in order to manipulate the cost model accordingly.

The extended optimization framework is depicted in Figure 3. The overall architecture can be seen as a two level optimization methodology (see Gantois and Morris [13]), altering the part design in the top level routine and optimizing process parameters in a lower level routine, the latter being termed *Process Adaptation Module* (PAM). PAM as an extension of the existing cost optimization routine has been realized with Matlab.

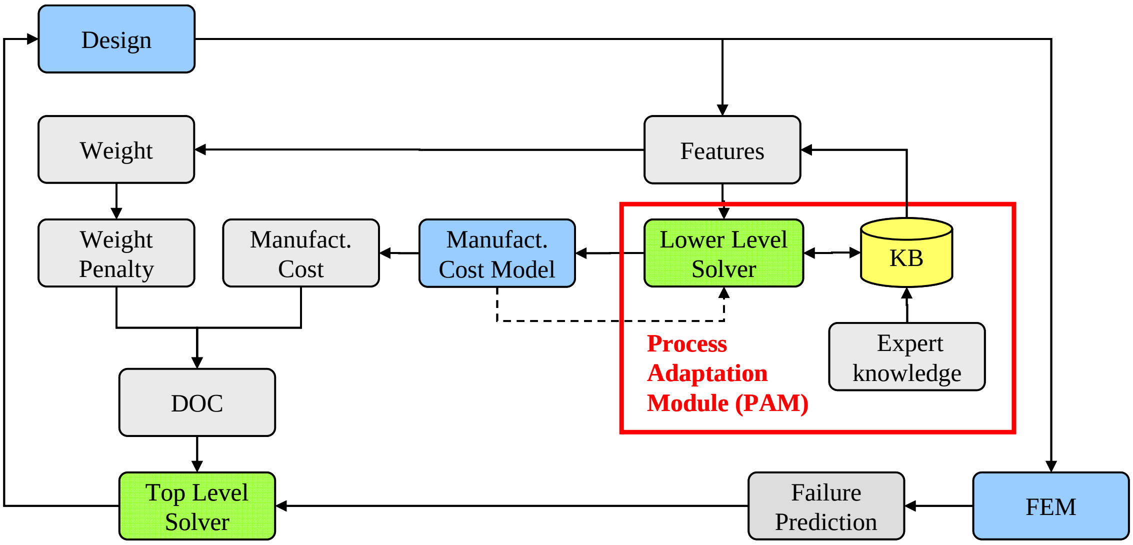

Figure 3: The extended optimization framework

3. CASE STUDY

Because of the high complexity of the optimization routine, it has been decided to show the effect of PAM by optimizing only two selective process features on a rear spar of an airliner's center wing box. Note that input data and results are purely academic and not related to any existent structure.

3.1 Part Design, Geometry and Materials

The design of the center wing box (CWB) rear spar is shown in Figure 4. The web of the spar can be separated into three sections; the rib 1 section, the far field section and the rib 6 section (see Table 1). This is done because the optimum design solution should be allowed to have a different thickness and fiber distribution in each section. The upper and lower edges are flanged for the attachment of the upper and lower CWB cover. Four vertical I-shaped stiffeners are attached to the outer side of the web and bolted to eight fittings at the inner side, the latter serving as the connection to the struts. Additionally, a manhole is positioned between the third and the fourth stiffener.

Based on this description, some geometric parameters are fixed, as shown in Table 1. Any other geometric data are not predefined and can potentially serve as design variables for the cost/weight optimization.

Two different materials are to be used for the main part components. The web is made of the composite laminate M21-T800s, while the vertical stiffeners and the internal fittings are made of aluminum alloy 7010, an alloy generally applied to high strength aerospace structural parts. The bolts used to fasten the stiffeners to the internal fittings are made of Ti6Al-4V.

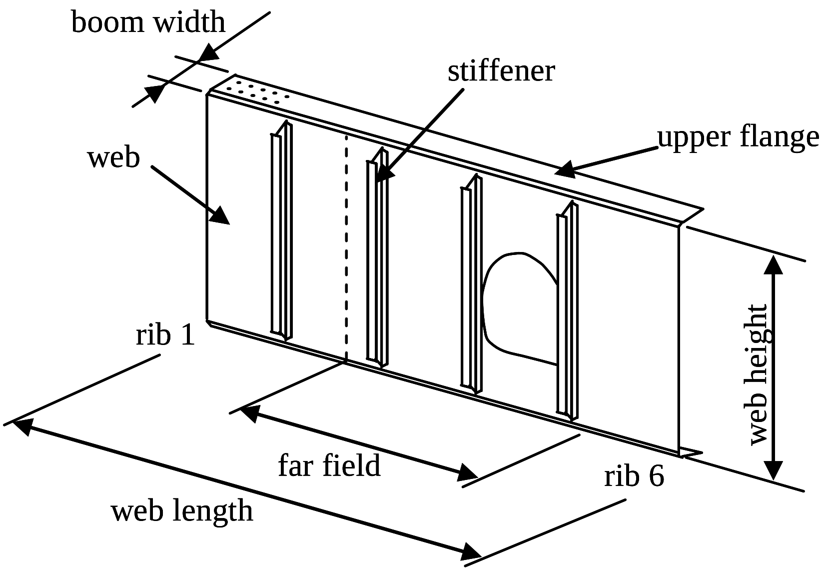

Figure 4: Outer side of the CWB rear spar

CWB geometric parameters	Description
Web length	2500 mm
Web height	909 mm
Boom width	300 mm
Stiffener length	809 mm
Stiffener foot height	6 mm
Stiffener distance	503 mm
Rib 1 section length	500 mm
Far field section length	1600 mm
Rib 6 section length	400 mm
Bolt diameter	6.35 mm
Ply thickness	0.26 mm

Table 1: Baseline geometry data for the CWB rear spar

3.2 Load Cases

The FE model is tested considering two load cases. These are

- an internal pressure load case (due to fuel overfilling) and
- a load case derived from the cabin pressure

Other test cases, such as turbulence (maximum upbend) and maneuver (maximum shear and downbend) have been neglected herein as they were regarded as non-critical.

3.3 Parameterization of the Rear Spar

The optimization procedure requires the parameterization of the structural model in terms of design variables x_i. Parameters that have a predictable behavior within the optimization were not selected as variables. The internal fittings, for instance, do not contribute much to the spar stiffness, strength and weight, and therefore their design should be kept unchanged.

Parameters of particular interest are the thickness of the spar and the geometry of the I-shaped stiffeners. Both components have a major impact on the spar strength and stiffness. The optimization is enhanced by the division of the web into three sections that may have different thicknesses, i.e. each section may have a different lay-up. Hence, a parameterization with 13 design variables is chosen as described in Table 2 and in Figure 5.

x_i	Description
x_1	Thickness of plies in 0° direction in Rib 1 section
x_2	Thickness of plies in 45° direction in Rib 1 section
x_3	Thickness of plies in 90° direction in Rib 1 section
x_4	Thickness of plies in 0° direction in far field section
x_5	Thickness of plies in 45° direction in far field section
x_6	Thickness of plies in 90° direction in far field section
x_7	Thickness of plies in 0° direction in Rib 6 section
x_8	Thickness of plies in 0° direction in Rib 6 section
x_9	Thickness of plies in 0° direction in Rib 6 section
x_{10}	Stringer height
x_{11}	Stringer width
x_{12}	Stringer flange thickness
x_{13}	Stringer pocket depth

Table 2: Design variables for the CWB rear spar

The constraints regarding the web lay-up (design variables x_1 to x_9) imply that the minimum thickness in each direction is at least two plies. The lower limit for the stringer height (x_{10}) and the upper limit for the stringer flange thickness (x_{12}) are adjusted in a way that the pocket height cannot be lower than the minimum cutter diameter (12 mm). Regarding the stringer pocket depth (x_{13}) a lower limit of 10 mm has been chosen for assembly reasons (6.35 mm fastener diameter). Finally, a constraint is included to avoid negative values for the pocket depth (x_{11}), while maintaining a minimum stringer web thickness of 6 mm.

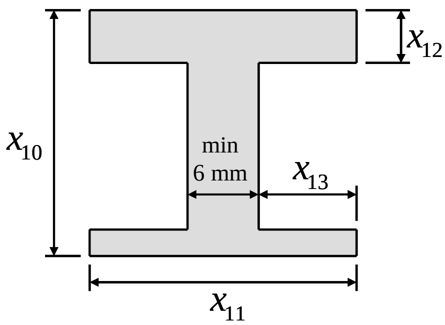

Figure 5: Stringer parameterization

This optimization problem can be rewritten as

$$\begin{aligned} \min_{x} \quad & C_{man}^{opt}(x,y) + p \cdot W(x) \qquad \text{where } y \text{ solves} \\ \min_{x|y} \quad & C_{man}^{opt}(x,y) \end{aligned} \tag{3}$$

subject to prescribed load case

$$0.52 < x_i < 10.00 \qquad x_i = 1...9$$

$$34.00 < x_{10} < 100.00$$

$$25.00 < x_{11} < 100.00$$

$$2.00 < x_{12} < 16.00$$

$$10.00 < x_{13} < 47.00$$

$$x_{13} < (x_{11} - 6)/2$$

$$y \in \text{parameter adjustments}$$

The selected process features for parameter adjustments y were two parameters for the pocket milling operations of the stiffeners, specifically the cutter diameter and the cutting tool material.

4. RESULTS

In the following, three optimization test runs are analyzed. The values for manufacturing cost and part weight are briefly addressed, followed by observations regarding the effects on the stringer milling process and the web lay-up. First implications regarding the optimization of the rear spar are given.

4.1 Manufacturing Cost and Weight

The total manufacturing cost and the part weight for the found optima are given in Table 3, where the weight penalty p (measured in € per kg) has been set to *0* in the *Cost only* test run, €1500/kg in the test run named *WP1500* and to infinity in the *Weight only* test run. The start values for the 13 design variables have been the same in each test run.

Test Run	Cost only	WP1500	Weight only
Manufacturing cost [€]	14996	15203	15657
Weight [kg]	76.89	70.59	70.10

Table 3: Optimum values of the test runs for cost/weight optimization of the CWB rear spar, using the extended optimization framework.

As could be expected, the manufacturing cost is the highest in the *Weight only* test run and lowest in the *Cost only* test run. The difference in manufacturing cost is about 4.4%. A similar behavior can be seen for the weight, *Weight only* resulting in the smallest manufacturing weight, followed by *WP1500* and *Cost only*. The difference in weight is about 9.7% for the two opposing solutions. The optimum design solution of *WP1500* was examined in SEER-DFM and the total manufacturing cost of the optimum design for the *WP1500* test run were allocated to labor, material, tooling and other costs, as illustrated in Figure 6.

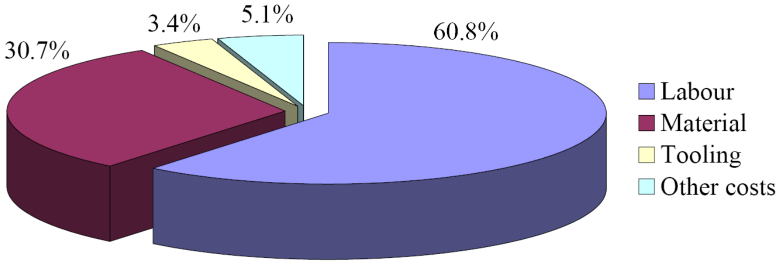

Figure 6: Cost allocation for the CWB rear spar at the *WP1500* test run optimum

Test Run	Cost only	WP1500	Weight only
Stringer Height [mm]	34.00	69.61	89.43
Stringer Width [mm]	26.00	98.37	98.22
Pocket Height [mm]	14.22	60.79	81.43
Pocket Depth [mm]	10.00	46.17	46.11
Cutter Diameter [mm]	12	32	32
Cutting Tool	C	C	C

Table 4: Selected parameters of the stringer geometry and the pocket milling operations according to the optimum design solutions

4.2 Stringer Milling Process

With respect to Table 4 it can be observed that the stringer height and the pocket height are increasing with a higher weight penalty, while stringer width and pocket depth are constant for high weight penalties.

Regarding the process adaptations made by PAM, it is notable that the cutter diameter changes when the stringer geometry changes. In the present cases, the optimum cutter diameter is the one closest below the pocket height, i.e. a 12 mm cutter for a pocket height of 14.22 mm and a 32 mm cutter for a pocket height of 60.79 and 81.43 mm, respectively. The cutting tool material was carbide for all design solutions. High speed steel (HSS) did not lead to a reduction in milling cost.

To analyze the effect of PAM, the cutter diameter and the cutting tool material have been set to values that are feasible for any design solution (12 mm, HSS) in the optimum SEER-DFM model for the *WP1500* test run. A closer look at the stringer manufacturing cost reveals that they can be reduced by 30% through the application of PAM. The share of this cost with respect to the total cost is 4.3% in that case. It is noteworthy that this reduction is achieved by optimizing only two process parameters, thereby indicating further cost saving potential for more complex aluminum structures.

4.3 Web Lay-up

The optimum data obtained for the web lay-up are given in Table 5. Note the change in the Rib 1 section, where the thickness of the web is reduced by 44% in favor of bulkier stiffeners.

Test Run	Cost only	WP1500	Weight only
Rib1 Section [mm]	9.36	5.22	5.51
Far Field Section [mm]	13.64	14.16	13.71
Rib6 Section [mm]	16.31	14.02	14.82

Table 5: Thicknesses of the three web sections and the corresponding weighted average values for the obtained optimum designs

It must be considered that the amount of data obtained with these test runs is not sufficient to draw reliable and detailed conclusions. The following items are of rather general nature. Beside the validation of the functionality of the extended framework, the test results given above indicate that

– the process adjustments made by PAM can lead to a significant reduction of the stringer manufacturing cost

- more process adjustments need to be optimized to achieve a significant reduction of the total manufacturing cost
- problems with local minima may arise during the optimization

5. CONCLUSION

The model approach has been formulated as an optimization problem which incorporates the manufacturing cost and the part weight in the objective function subject to structural requirements and design variables.

The Process Adaptation Module is a first step towards the sub-optimization of manufacturing processes. It provides the most cost-efficient set of cutter diameter and cutting tool material to be chosen for the machining of aluminum stringers.

It has to be considered that the integration of PAM into the existing framework significantly extends the calculation time of an optimization run. Another special tool or an enhancement of Xopt is therefore needed to reduce the number of invocations of SEER-DFM in the lower level optimization.

Nevertheless, first test runs have shown the functionality of the integrated framework with an upper level routine (Xopt) and a lower level routine (PAM) for cost optimization of the CWB rear spar. Additionally it has to be noted that PAM has been developed using a modular script structure and may therefore be easily extended or included in other structural optimization problems that incorporate SEER-DFM. If tailored to parts whose geometry and manufacturing processes are not predefined to a high degree, it may have a major impact.

6. FUTURE WORK

A way for reducing computing time of Process Adaptation Module has to be found, especially when more process features are to be processed. PAM should further be modified and tailored to the optimization of other parts and manufacturing methods, with a special focus on composite structures.

Regarding the cost model, the possibility for the inclusion of maintenance, repair and overhaul (MRO) cost with respect to composite parts has to be investigated.

7. ACKNOWLEDGMENTS

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